Realization of Principle of Power Deliveries Settlement for Large Scale High Voltage Electric Power Network

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Abstract: – The development of free access market interrelations requires for the operation of power systems the examination of the new criteria for the economic estimation of the behavior of the participants of market. Hence, more actual becomes the problem of the determination of the shared contribution of each power source in the supply of concrete load and determination of the corresponding power flows and losses in power network lines. This information is necessary for determining the substantiated price for the electric power, obtained by concrete user. Based on the example of the graph of the 330 kV network of Latvian power system, four versions of the supply of concrete user in the dependence on a change of supplier (taking into account the existing intersystem connections of the power system of Latvia) is examined. The obtained results can serve as source material for the analysis of a question about the establishment of price of the obtained electric power.

Key words: – Power systems, Graph theory, Settlement factors, Transmission loss allocation

1. Introduction

Distribution of active and reactive power of generators between the customers raises a problem of contribution of each power plant in supplying the specific load and determining power flow from each generator through the branches of an electric power network lines. An algorithm that enables the problem mentioned above to be solved for large-scale power networks is proposed.

The contribution of each power plant in supplying the specific load and determination of power flow from each generator through the branches of power network is very important to determine:

- price of electrical power in nodes of power network
- responsibility for the relevance of losses in the electric power network elements;
- charge for transit;
- electric power price correction taking in account the losses and several other tasks.

The interest to this problem is growing by development of free access market in operations of electric power systems.

The main issues reviewed in paper are:

- a method to determine settlement factors, based on search for path on an oriented graph that allows to determine share of active or reactive power transmitted from each generator node along the branches of electric power network to the load nodes;
- approbation of decomposing power losses in the network elements at power transfer from generator nodes to load nodes.

It can be explained as follows. Presume that power P_{gi} produced by the i-th generator is market with label p_i, so it could not be mixed with another power produced by j-th generator, which is marked with label p_j.

If trough the same element of the electric power network is flowing two or more power flows, which are marked with the same label, then these flows are summed.

In recent years many papers are published in which both matrix and graph algorithm for solution of contribution tasks have been used [1 – 6].

2. A Method for Loss Calculation

Let us determine n components of power flow S_l in branch l:

$$S_l = \sum_{i=1}^{n} S_{l_i} , \quad (1)$$

where: S_{li} – share of i-th generator in power flow S_l .

Then losses of active power in l-th branch, with resistance r_l, can be written as:

$$\Delta P_l = S_l^2 \frac{r_l}{U_l^2} , \quad (2)$$

where U_l – branch l average voltage.

Considering (1), we obtain:

$$\Delta P_l = \left(\sum_{i=1}^{n} S_{l_i}\right)^2 \frac{r_l}{U_l^2} = \sum_{i=1}^{n} \frac{S_{l_i}^2}{U_l^2} r_l + \sum_{i=1}^{n}\sum_{\substack{j=1\\ i\neq j}}^{n} S_{l_i} S_{l_j} \frac{r_l}{U_l^2} =$$

$$= \Delta P_{l1} + \Delta P_{l2}, \quad (3)$$

where ΔP_{l1} – own losses from i-th generator, but ΔP_{l2} – common losses [6].

Problem occurs in contribution of common losses; different methods of solution are proposed [2 – 6], based on various arrangements for its settlement.

However, if the difference between power flows in beginning and end of branch is used for determining the losses in branch is

$$\Delta P_l = P_{lbeg.} - P_{lend.}, \quad (4)$$

then sum of losses from n power flows will be equal with real losses in this branch:

$$\sum_{i=1}^{n} \Delta P_l = \sum_{i=1}^{n} P_{libeg.} - P_{liend.} = \Delta P_l . \quad (5)$$

Furthermore, it is no need to make any arrangements for contribution of losses in branches of electric power network, it is enough to know only the power flow in the beginning and end of the branches transmitted from the generators.

3. Algorithm of Settlement Factors

Detailed concept of the algorithm for determining settlement factors of power flows and losses are proposed in [7 – 9]. According to that, as an oriented graph we use power flow contribution, which is obtained using computer program for stationary regime calculation of electric power systems "Mustang". Power losses in individual branches and total power losses can also be determined.

Before the algorithm starts, the initial relative power flows of beginning and end of each branch are determined. A relative flow is equal to the relationship between the flow in the beginning (end) of the branch and the total power transmitted from the initial node of the branch. The value of a relative flow of the beginning (end) of the branch shows what share of the power from the initial node of the branch is transferred by the flow of the beginning (end) of the branch. New values of relative flows in the branches are calculated when constructing the tree in the branches connecting the previous and subsequent tiers of the j-th path in the tree, starting with the second branch k = 2, that connects the second and the third tiers.

Let $\overline{P}_{ibeg}(\overline{P}_{iend})$ – be an initial value of a relative flow of the beginning (end) of the branch i. ; $\overline{P}^k_{jibeg}(\overline{P}^k_{jiend.})$ – a new value of a relative flow of the beginning (end) of the branch i, that is a k-th branch of the j-th path in tree and is located between the k-th and k + 1-th tiers, $k > 1$; for $k = 1$ $\overline{P}^k_{jibeg} = \overline{P}_{ibeg.}$, and $\overline{P}^k_{jiend.} = \overline{P}_{iend.}$

The new value of the relative flow in the end of the branch i, that is the k-th branch of the j-th path in the tree will be determined as

$$\overline{P}_{jiend} = \overline{P}^{k-1}_{jend}\overline{P}_{iend} = \prod_{m-1}^{k-1} \overline{P}^m_{jend}\overline{P}_{ibeg}, \quad (6)$$

where $\overline{P}^{k-1}_{jend}$ – is a value of the relative flow in the end of the end of the branch (k-1) preceding the branch i on the j-th path; $\overline{P}^m_{jend}$, m =1, k – 1 – are initial values of relative flows of the ends of the k – 1 branches of the j-th path.

For the relative flow in the beginning of the branch i the new values will be equal to

$$\overline{P}^k_{jibeg} = \overline{P}^{k-1}_{jend}\overline{P}_{ibeg.} = \prod_{m-1}^{k-1} \overline{P}^m_{jend}\overline{P}_{ibeg}, \quad (7)$$

The resulting values of relative flows of the end and beginning of the branch i, belonging to L paths in the tree, can be determined as

$$\overline{P}_{iend} = \sum_{j=1}^{L}\prod_{m=1}^{k_j-1} \overline{P}^m_{jend}\overline{P}_{iend}; \quad (9)$$

$$\overline{P}_{ibeg.} = \sum_{j=1}^{L}\prod_{m=1}^{k_j-1} \overline{P}^m_{jend}\overline{P}_{ibeg}. \quad (10)$$

where index k_j in all equations corresponds to the ordinal number of the branch i on the j-th path in the tree.

The relative power flows (9 – 10) show the share of power generated by generator node, which flows in branch i, therefore they are called settlement factors $A_{fl_{mi}}$ of the flow in the branch i from the generator node m.

Settlement factor is non-dimension magnitude. By multiplying this factor by generated power we obtain the share of the generator power transmitted in the branch i and this share has dimension of the power.

4. An Example of Settlement Factors Algorithm Realization.

Let us consider an example to illustrate the work of the settlement factors algorithm for active load flow contribution that was obtained based on estimations of computer program "Mustangs" for stationary regime calculations [10]. The calculations are made for real existing large-scale power network – 330 kV power system of Latvia. Rough representation of the

Latvia 330 kV power system is presented in Fig. 1. There are 14 330 kV substations and 7 intersystem connections with neighbor power systems (Lithuania, Russia, and Estonia) in Latvia, which are shown in Fig 1. As input data for stationary regime calculations serves technical parameters of power network and power values of generating and load nodes. The intersystem connections are represented by the set values of generated or consumed power.

Four different power flow regimes are examined. First regime is a base regime. For the second regime the load in substation "Grobiņa" (2) has been increased by 20 MW, which is provided, by the increase of the deliveries from Estonia power system. For the third and fourth regimes there is the same increase of load in substation "Grobiņa" (2), but it is provided with increase of deliveries from Russian and Lithuanian power systems accordingly.

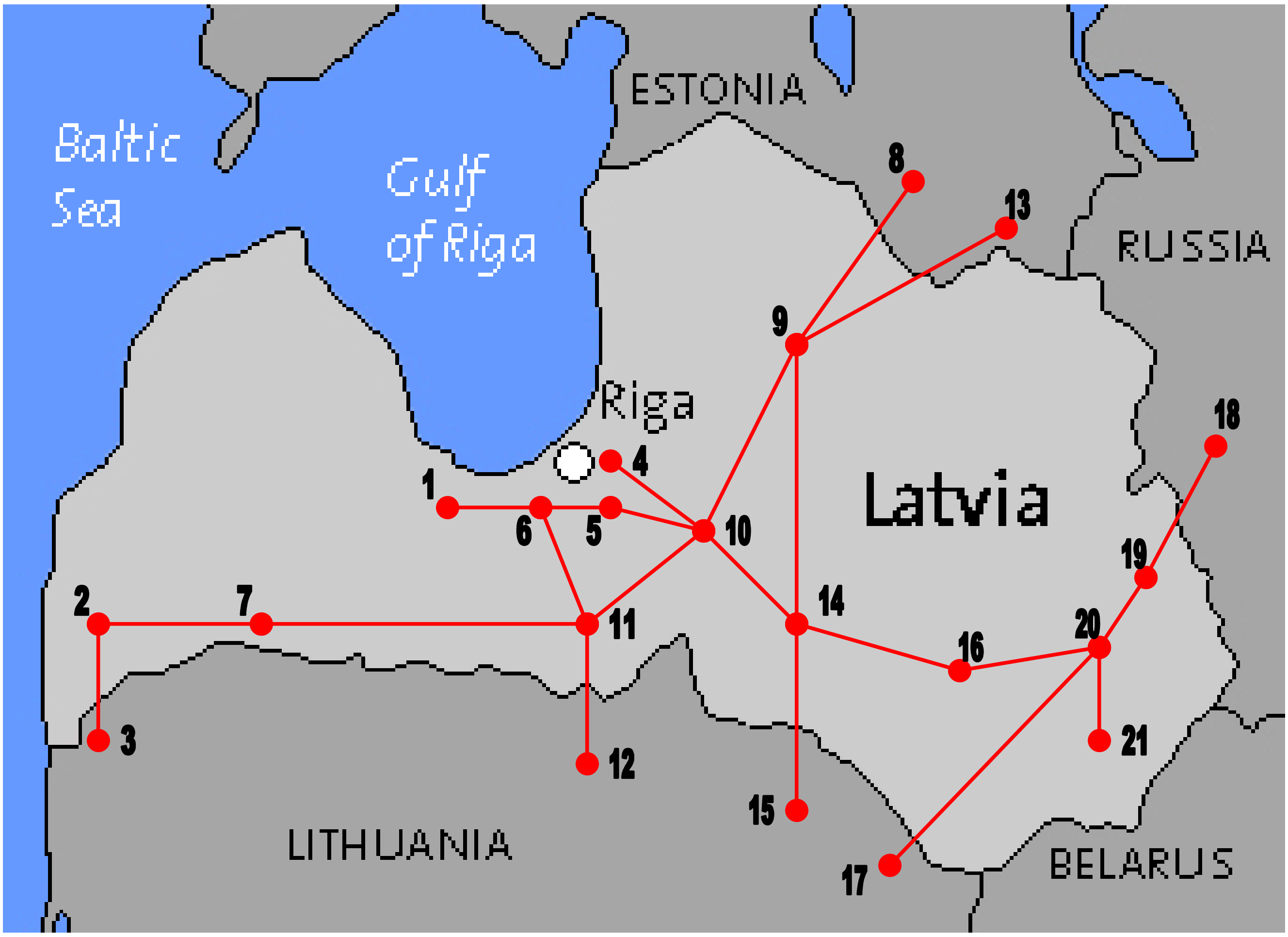

Fig 1. 330 kV power network of Latvia

Fig. 2 shows an equivalent circuit of Latvia 330 kV power network. Initial values of power flow for the beginning and end of the branches as well as power of generating nodes and load nodes for the first regime are shown as figures (unit of figures is MW). The trend of load flow in branches is also shown.

Stations and substations are represented as follows: 1 – Imanta; 2 – Grobiņa; 3 – Klaipeda; 4 – Riga TPP; 5 – Riga HPP; 6 – Bišuciems; 7 – Brocēni; 8 – Tartu; 9 – Valmiera; 10 – Salaspils; 11 – Jalgava; 12 – Šauļi; 13 – Tsirgulina; 14 – Pļviņas HPP; 15 – Paņevežis; 16 – Krustpils; 17 – Ignalina NPP; 18 – Veļikoreckaja; 19 – Rēzekne; 20 – Līksna; 21 – Daugavpils. Nodes 5, 8, 13, 14, 17, and 18 are generating nodes.

Prior start of using the settlement factors determining algorithm, relative flows for the beginning and end of branches are calculated.

The results of active load flow decomposition for two branches presented in Table 1 show settlement factors of flows and losses along with power flows and losses in the branches in correspondence with each generator. It is visual that the values of power flows and losses in the branches coincide with the initial load flows. The calculations for all branches and regimes has been done, but not shown in table.

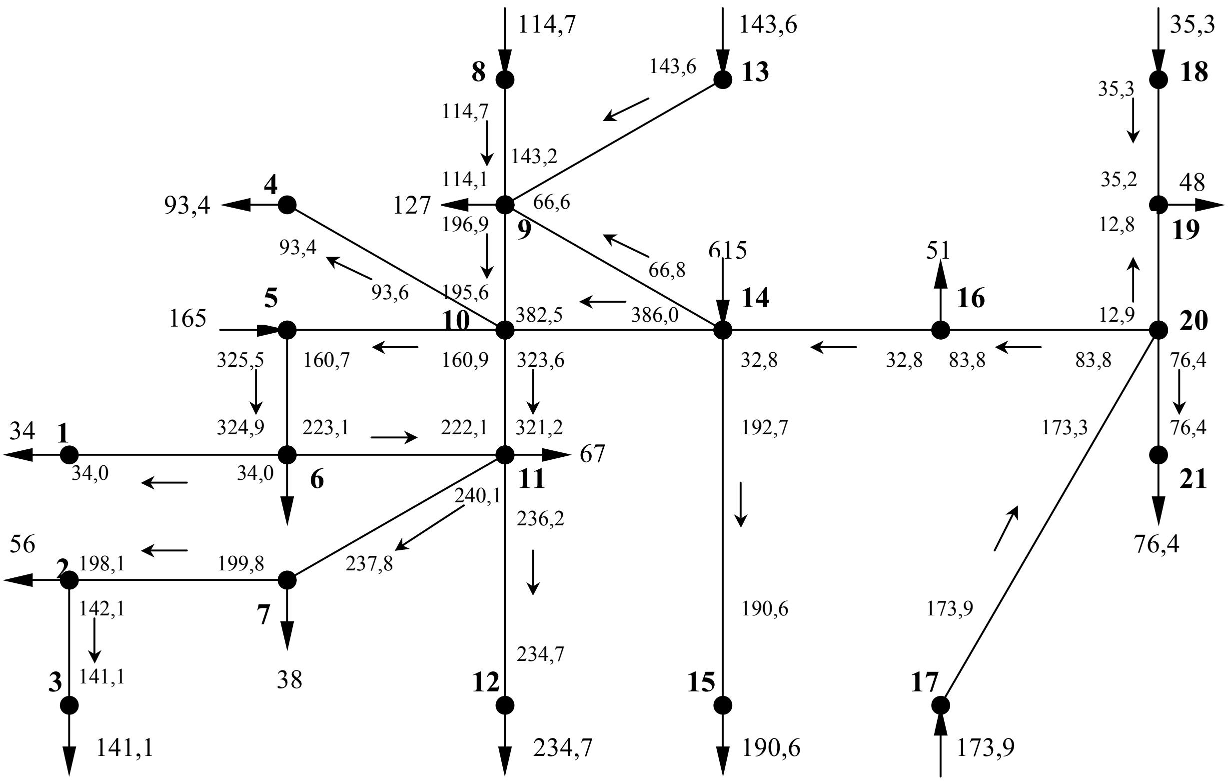

Fig. 2. Latvia 330 kV network equivalent circuit with values and directions of power flows.

Table 1. Settlement factors of active power flows and losses in branches

Branch i	Settlement factors of active power flows and losses												Σ, MW
	G5		G8		G13		G14		G17		G18		
	A_{f5i}	$A_{f5i}{\cdot}P_5$	A_{f8i}	$A_{f8i}{\cdot}P_8$	A_{f13i}	$A_{f13i}{\cdot}P_{13}$	A_{f14i}	$A_{f14i}{\cdot}P_{14}$	A_{f17i}	$A_{f17i}{\cdot}P_{17}$	A_{f18i}	$A_{f18i}{\cdot}P_{18}$	
Regime 1													
7 - 2 beg.	0.2509	41.35	0.1646	18.89	0.1651	23.70	0.1795	109.97	0.0338	5.89	-	-	199.8
end	0.2488	41.00	0.1632	18.72	0.1636	23.50	0.1779	109.04	0.0336	5.84	-	-	198.1
losses	0.0021	0.35	0.0014	0.16	0.0014	0.20	0.0015	0.94	0.0003	0.05	-	-	1.7
11 - 7 beg.	0,3015	49,69	0,1979	22,69	0,1983	28,48	0,2157	132,16	0,0407	7,07	-	-	240.1
end	0,2987	49,22	0,1960	22,48	0,1964	28,21	0,2136	130,89	0,0403	7,01	-	-	237.8
losses	0,0029	0,48	0,0019	0,22	0,0019	0,27	0,0021	1,27	0,0004	0,07	-	-	2.3
Regime 2													
7 - 2 beg.	0,2641	43,52	0,1756	21,21	0,1760	26,35	0,1886	115,54	0,0388	6,77	-	-	213,4
end	0,2619	43,16	0,1741	21,03	0,1745	26,13	0,1870	114,57	0,0385	6,71	-	-	211,6
losses	0,0022	0,37	0,0015	0,18	0,0015	0,22	0,0016	0,97	0,0003	0,06	-	-	1,8
11 - 7 beg.	0,3134	51,64	0,2084	25,17	0,2088	31,26	0,2237	137,09	0,0461	8,03	-	-	253,2
end	0,3111	51,27	0,2069	24,99	0,2074	31,04	0,2221	136,12	0,0458	7,97	-	-	251,4
losses	0,0022	0,37	0,0015	0,18	0,0015	0,22	0,0016	0,97	0,0003	0,06	-	-	1,8
Regime 3													
7 - 2 beg.	0,2637	43,46	0,1751	20,91	0,1755	25,94	0,1888	115,72	0,0395	6,97	-	-	213
end	0,2615	43,09	0,1737	20,73	0,1741	25,73	0,1872	114,74	0,0392	6,91	-	-	211,2
losses	0,0022	0,37	0,0015	0,18	0,0015	0,22	0,0016	0,98	0,0003	0,06	-	-	1,8
11 - 7 beg.	0,3135	51,66	0,2082	24,86	0,2087	30,84	0,2245	137,55	0,0470	8,28	-	-	253,2
end	0,3108	51,22	0,2064	24,64	0,2069	30,57	0,2225	136,36	0,0466	8,21	-	-	251
losses	0,0027	0,45	0,0018	0,22	0,0018	0,27	0,0020	1,20	0,0004	0,07	-	-	2,2
Regime 4													
7 - 2 beg.	0,2629	43,33	0,1743	20,24	0,1746	25,32	0,1892	115,94	0,0386	6,87	-	-	211,7
end	0,2607	42,97	0,1729	20,07	0,1731	25,10	0,1876	114,95	0,0383	6,81	-	-	209,9
losses	0,0022	0,37	0,0015	0,17	0,0015	0,22	0,0016	0,99	0,0003	0,06	-	-	1,8
11 - 7 beg.	0,3131	51,60	0,2076	24,10	0,2079	30,15	0,2253	138,06	0,0460	8,18	-	-	252,1
end	0,3101	51,11	0,2056	23,87	0,2060	29,86	0,2232	136,75	0,0455	8,10	-	-	249,7
losses	0,0030	0,49	0,0020	0,23	0,0020	0,29	0,0021	1,31	0,0004	0,08	-	-	2,4

After the settlement factors and power flow values in the branches of trees are determined for each generator node, it is possible to determine settlement factors associated with generator power transfer to the load nodes. Fig. 3 shows one of the oriented graphs - trees for this power system equivalent circuit. According to the tree shown in Fig. 3 the path from generator to load nodes has been searched, to calculate settlement factors of power transfer and losses.

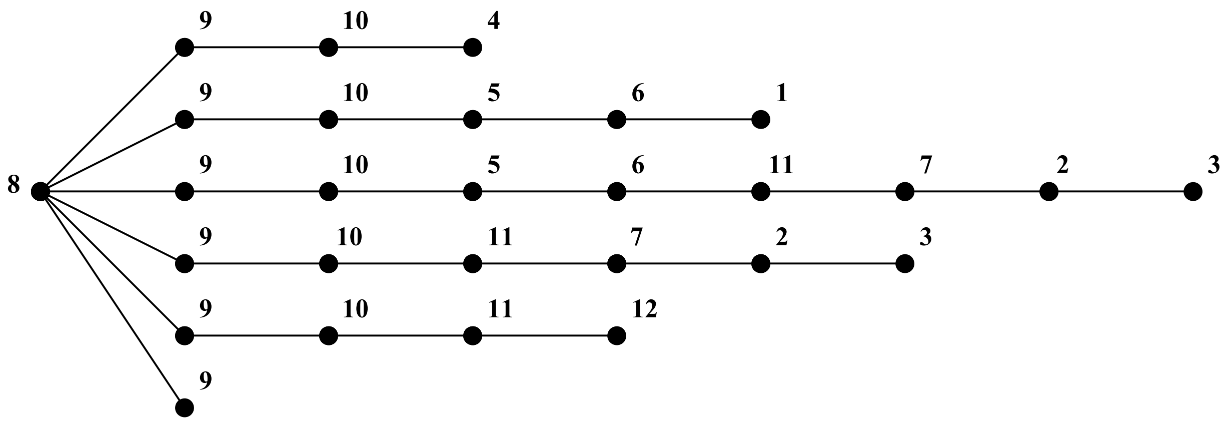

Fig. 3. Orientated graph – tree with generator node 8 as a base.

Table.2: Settlement factors of active power transfer and losses

Node i	Settlement factors of active power flows and losses												Σ, MW
	G5		G8		G13		G14		G17		G18		
	A_{f5i}	$A_{f5i}{\cdot}P_5$	A_{f8i}	$A_{f8i}{\cdot}P_8$	A_{f13i}	$A_{f13i}{\cdot}P_{13}$	A_{f14i}	$A_{f14i}{\cdot}P_{14}$	A_{f17i}	$A_{f17i}{\cdot}P_{17}$	A_{f18i}	$A_{f18i}{\cdot}P_{18}$	
Regime 1													
2 transm.	0,0721	11,88	0,0479	5,50	0,0479	6,88	0,0521	31,92	0,0099	1,72	-	-	57,89
received	0,0703	11,59	0,0461	5,29	0,0463	6,64	0,0503	30,82	0,0095	1,65	-	-	56,00
losses	0,0017	0,29	0,0018	0,20	0,0017	0,24	0,0018	1,09	0,0004	0,07	-	-	1,89
7 transm.	0,0485	7,99	0,0322	3,70	0,0322	4,63	0,0350	21,47	0,0066	1,16	-	-	38,95
received	0,0477	7,86	0,0313	3,59	0,0314	4,51	0,0341	20,92	0,0064	1,12	-	-	38,00
losses	0,0008	0,13	0,0009	0,11	0,0008	0,12	0,0009	0,56	0,0002	0,04	-	-	0,95
Regime 2													
2 transm.	0,0962	15,85	0,0649	7,83	0,0649	9,71	0,0694	42,55	0,0144	2,51	-	-	78,45
received	0,0941	15,50	0,0625	7,55	0,0627	9,38	0,0672	41,15	0,0138	2,41	-	-	76,00
losses	0,0021	0,35	0,0023	0,28	0,0022	0,33	0,0023	1,40	0,0006	0,10	-	-	2,45
7 transm.	0,0477	7,86	0,0322	3,88	0,0322	4,81	0,0344	21,10	0,0071	1,24	-	-	38,90
received	0,0470	7,75	0,0313	3,78	0,0313	4,69	0,0336	20,58	0,0069	1,21	-	-	38,00
losses	0,0007	0,11	0,0009	0,11	0,0008	0,12	0,0009	0,52	0,0002	0,04	-	-	0,90
Regime 3													
2 transm.	0,0964	15,88	0,0649	7,74	0,0649	9,59	0,0697	42,74	0,0147	2,60	-	-	78,55
received	0,0941	15,51	0,0625	7,46	0,0626	9,26	0,0674	41,29	0,0141	2,49	-	-	76,00
losses	0,0023	0,37	0,0024	0,28	0,0022	0,33	0,0024	1,45	0,0006	0,11	-	-	2,55
7 transm.	0,0478	7,87	0,0322	3,84	0,0322	4,75	0,0346	21,19	0,0073	1,29	-	-	38,94
received	0,0470	7,75	0,0312	3,73	0,0313	4,63	0,0337	20,64	0,0071	1,24	-	-	38,00
losses	0,0007	0,12	0,0009	0,11	0,0008	0,12	0,0009	0,55	0,0002	0,04	-	-	0,94
Regime 4													
2 transm.	0,0968	15,95	0,0649	7,53	0,0649	9,41	0,0703	43,09	0,0144	2,57	-	-	78,55
received	0,0944	15,56	0,0626	7,27	0,0627	9,09	0,0679	41,62	0,0139	2,47	-	-	76,00
losses	0,0024	0,39	0,0023	0,27	0,0022	0,32	0,0024	1,46	0,0006	0,10	-	-	2,55
7 transm.	0,0480	7,91	0,0322	3,73	0,0322	4,66	0,0349	21,36	0,0072	1,27	-	-	38,94
received	0,0472	7,78	0,0313	3,63	0,0313	4,54	0,0340	20,81	0,0069	1,23	-	-	38,00
losses	0,0008	0,13	0,0009	0,10	0,0008	0,12	0,0009	0,55	0,0002	0,04	-	-	0,94

Table 2 presents settlement factors of transfer of power from the generating nodes to the load nodes and share of contribution of each generating node in supplying the specific load. The values in the last column prove validity of the obtained decomposition i.e. the values of power in the load nodes and generator nodes coincide and the total values of power losses coincide, too.

The results of calculations are shown only for two nodes 2 and 7, but the settlement factors and share of contribution of each generating node in supplying each load node are determined for all nodes and all regimes.

5. Settlement Factors of Reactive Power

There is very little difference between the settlement factors problem solution for active and reactive power allocation. The difference consists mainly in the need to take into account the capacity admittances of branches, included into a Π-shaped equivalent circuit of transmission lines and inductive admittances of transformers belonging to their Γ-shaped equivalent circuit.

Unlike the presentation of such admittances that was assumed in the programs for electric power systems stationary regime calculation let us introduce capacitance and inductance shunts into the information on the node instead of admittances of transmission lines and transformers respectively.

6. Conclusions

The possibility for determining power flow contribution from each generator to specific load in power system has been examine for real existing large scale power system.

Performed calculations for concrete electric power system testify prospectivity of settlement algorithms in conditions of developing financially – economical relations between participants of power market.

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