

APPLICATION OF PRINCIPLE OF POWER DELIVERIES SETTLEMENT FOR 330 KV ELECTRIC POWER NETWORK

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Abstract. *Distribution of active and reactive power between consumers raises the problem of participation of each power station in supply of loads and determining flows of power from each generator through branches of an electric power network. Interest of this problem mainly is chosen by the development of open access market in power systems. In this paper a method is reviewed of determination of settlement factors, which is based on finding the trace in oriented graph, and allows, with the number of cycles equal with the number of generator nodes, determine the part of active power, which flow from each generator through branches of electric network to load node.*

Keywords: graph theory, settlement factor, 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 equivalent circuit. An algorithm that enables the problem mentioned above to be solved for large-scale power networks is proposed [1-4].

The contribution of each power plant in supplying the specific load and determination of power flow from each generator through the branches of an electric power network equivalent, 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 [5-6].

The issues reviewed in paper are:

- a method to determine settlement factors, based on search for path on a directed graph that allows to determine share, or 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 transmission from generator nodes to load nodes.

It can be explained as follows. Presume that power P_{gi} produced by the i -th generator is marked 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 through 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 [7-9].

2. A METHOD FOR LOSS CALCULATION

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

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

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:

$$\begin{aligned} \Delta P_l &= \left(\sum_{i=1}^n S_{li} \right)^2 \frac{r_l}{U_l^2} = \\ &= \sum_{i=1}^n \frac{S_{li}^2}{U_l^2} r_l + \sum_{i=1}^n \sum_{\substack{j=1 \\ i \neq j}}^n S_{li} S_{lj} \frac{r_l}{U_l^2} = \Delta P_{l1} + \Delta P_{l2} \end{aligned} \quad (3)$$

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:

$$\Delta P_l = P_{libeg.} - P_{liend.} \quad (4)$$

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. AN 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:

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

where $\bar{P}_{jend}^{k-1}$ – 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; $\bar{P}_{jend}^m$, $m=1, k-1$ – 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:

$$\bar{P}_{jibeg}^k = \bar{P}_{jend}^{k-1} \bar{P}_{ibeg} = \prod_{m=1}^{k-1} \bar{P}_{jend}^m \bar{P}_{ibeg} \quad (7)$$

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

$$\bar{P}_{iend} = \sum_{j=1}^L \prod_{m=1}^{k_j-1} \bar{P}_{jend}^m \bar{P}_{iend} \quad (8)$$

$$\bar{P}_{ibeg} = \sum_{j=1}^L \prod_{m=1}^{k_j-1} \bar{P}_{jend}^m \bar{P}_{ibeg} \quad (9)$$

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 (8 – 9) show the share of power generated by generator node, which flows in branch i , therefore they are called settlement factors 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 first 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 first 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 first node of the branch is transferred by the flow 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 earlier and next 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 $\bar{P}_{ibeg} (\bar{P}_{iend})$ – be an initial value of a relative flow of the beginning (end) of the branch i ; $\bar{P}_{jibeg}^k (\bar{P}_{jiend}^k)$ – 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 $k = 1$ $\bar{P}_{jibeg}^k = \bar{P}_{ibeg}$, and $\bar{P}_{jiend}^k = \bar{P}_{iend}$.

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 found as $A_{fl_{mi}}$ of the flow in the branch i from the generator node m .

Settlement factor is non-dimension size. 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 IMPLEMENTATION

Let us consider an example to illustrate the work of the settlement factors algorithm for active load flow that was obtained based on estimations of computer program

“Mustangs” for stationary regime calculations [10]. Figure 1 shows an equivalent circuit of Latvia 330 kV electric power network. Initial values of power flow for the beginning and end of the branches as well as power of generators and loads are shown as figures (unit of these figures is MW). The trend of load flow in branches is also shown in Figure 1.

The results of active load flow decomposition for several branches presented in Table 1 show settlement factors of flows and losses along with power flows and losses in the branches connected with each generator. It is visual that the values of power flows and losses in the branches coincide with the first load flows.

Nodes 5, 8, 13, 14, 17, and 18 are generator nodes.

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

TABLE 1. Settlement factors of active power flows and losses for several branches.

Branch i	Settlement factors of active power flows and losses												Σ MW
	G5		G8		G13		G14		G17		G18		
	A_{f5i}	$A_{f5i}P_5$	A_{f8i}	$A_{f8i}P_8$	A_{f13i}	$A_{f13i}P_{13}$	A_{f14i}	$A_{f14i}P_{14}$	A_{f17i}	$A_{f17i}P_{17}$	A_{f18i}	$A_{f18i}P_{18}$	
2 – 3 beg. end losses	0,1785	29,45	0,1171	13,43	0,1174	16,86	0,1277	78,51	0,0241	4,19			142,43
	0,1772	29,24	0,1163	13,34	0,1166	16,74	0,1268	77,95	0,0239	4,16			141,43
	0,0013	0,21	0,0008	0,09	0,0008	0,12	0,0009	0,55	0,0002	0,03			1,00
5 - 6 beg. end losses	1,0000	165,00	0,1670	19,15	0,1674	24,04	0,1820	111,96	0,0343	5,97			326,12
	0,9982	164,70	0,1667	19,12	0,1676	24,07	0,1817	111,75	0,0343	5,96			325,59
	0,0018	0,30	0,0003	0,04	0,0003	0,04	0,0003	0,21	0,0001	0,01			0,60
6 - 1 beg. end losses	0,1045	17,24	0,0174	2,00	0,0175	2,51	0,0190	11,69	0,0036	0,62			34,06
	0,1045	17,24	0,0174	2,00	0,0175	2,51	0,0190	11,69	0,0036	0,62			34,06
	0,0000	0,00	0,0000	0,00	0,0000	0,00	0,0000	0,00	0,0000	0,00			0,00
6 - 11 beg. end losses	0,6854	113,09	0,1145	13,13	0,1147	16,48	0,1248	76,73	0,0235	4,09			223,52
	0,6823	112,59	0,1139	13,07	0,1142	16,40	0,1242	76,39	0,0234	4,07			222,52
	0,0031	0,51	0,0005	0,06	0,0005	0,07	0,0006	0,34	0,0001	0,02			1,00
7 - 2 beg. end losses	0,2509	41,40	0,1646	18,89	0,1651	23,70	0,1795	110,39	0,0339	5,89			200,26
	0,2488	41,05	0,1632	18,72	0,1636	23,50	0,1780	109,45	0,0336	5,84			198,56
	0,0021	0,35	0,0014	0,16	0,0014	0,20	0,0015	0,94	0,0003	0,05			1,70
8 - 9 beg. end losses			1,0000	114,70									114,70
			0,9948	114,10									114,10
			0,0052	0,60									0,60
9 - 10 beg. end losses			0,6047	69,36	0,6062	87,05	0,0627	38,57	0,0118	2,06			197,04
			0,6007	68,90	0,6022	86,48	0,0623	38,32	0,0118	2,04			195,74
			0,0040	0,46	0,0040	0,57	0,0004	0,25	0,0001	0,01			1,30
10 - 4 beg. end losses			0,0973	11,16	0,0975	14,00	0,1060	65,21	0,0200	3,48			93,84
			0,0971	11,13	0,0973	13,97	0,1058	65,07	0,0200	3,47			93,64
			0,0002	0,02	0,0002	0,03	0,0002	0,14	0,0000	0,01			0,20
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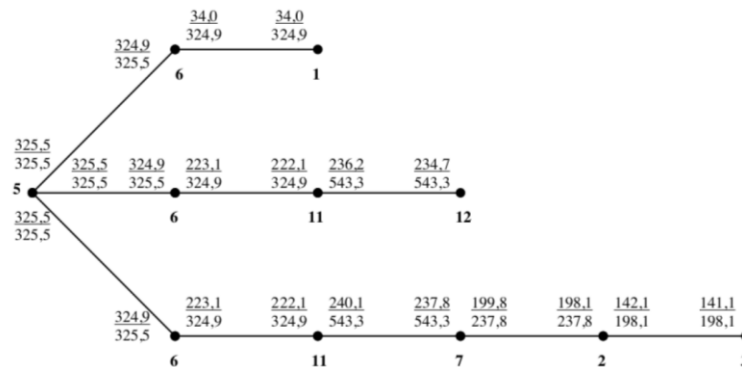


Figure 1. Orientated graph – tree with generator node 5 as a base.

After the settlement factors and 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. Figure 1 shows one of the trees for this power system equivalent circuit.

According to the tree shown in Figure 1 the path from generator to load nodes has been searched, to calculate settlement factors of power transfer and losses.

Calculations of settlement factors for path from generator node 5 to load node 6:

Settlement factor for the transmitted power from generator node 5:

$$\frac{325,5}{325,5} \cdot \frac{67,8}{325,5} = 0,2087$$

Settlement factor for received power in load node 6:

$$\frac{324,9}{325,5} \cdot \frac{67,8}{325,5} = 0,2083$$

Settlement factor for loss of power during transfer:

$$0,2087 - 0,2083 = 0,0004$$

Calculations of settlement factors for path from generator node 5 to load node 1:

Settlement factor for the transmitted power from generator node 5:

$$\left(\frac{325,5}{325,5} \cdot \frac{34}{324,9} \right) \cdot \frac{34}{34} = 0,1046 ;$$

Settlement factor for received power in load node 1:

$$\left(\frac{324,9}{325,5} \cdot \frac{34}{324,9} \right) \cdot \frac{34}{34} = 0,1045 ;$$

Settlement factor for loss of power during transfer:

$$0,1046 - 0,1045 = 0,0001$$

Calculations of settlement factors for path from generator node 5 to load node 7:

Settlement factor for the transmitted power from generator node 5:

$$\left(\frac{325,5}{325,5} \cdot \frac{223,1}{324,9} \cdot \frac{240,1}{543,3} \right) \cdot \frac{38}{237,8} = 0,0485 ;$$

Settlement factor for received power in load node 7:

$$\left(\frac{324,9}{325,5} \cdot \frac{222,1}{324,9} \cdot \frac{237,4}{543,3} \right) \cdot \frac{38}{237,8} = 0,0477 ;$$

Settlement factor for loss of power during transfer:

$$0,0485 - 0,0477 = 0,0008 .$$

Calculations of settlement factors for path from generator node 5 to load node 2:

Settlement factor for the transmitted power from generator node 5:

$$\left(\frac{325,5}{325,5} \cdot \frac{223,1}{324,9} \cdot \frac{240,1}{543,3} \cdot \frac{199,8}{237,4} \right) \cdot \frac{56}{198,1} = 0,0721 ;$$

Settlement factor for received power in load node 2:

$$\left(\frac{324,9}{325,5} \cdot \frac{222,1}{324,9} \cdot \frac{237,4}{543,3} \cdot \frac{198,1}{237,4} \right) \cdot \frac{56}{198,1} = 0,0703 ;$$

Settlement factor for loss of power during transfer:

$$0,0721 - 0,0703 = 0,0018 .$$

Calculations of settlement factors for path from generator node 5 to load node 3:

Settlement factor for the transmitted power from generator node 5:

$$\left(\frac{325,5}{325,5} \cdot \frac{223,1}{324,9} \cdot \frac{240,1}{543,3} \cdot \frac{199,8}{237,4} \cdot \frac{142,1}{198,1} \right) \cdot \frac{141,1}{141,1} = 0,1046 ;$$

Settlement factor for received power in load node 3:

$$\left(\frac{324,9}{325,5} \cdot \frac{222,1}{324,9} \cdot \frac{237,4}{543,3} \cdot \frac{198,1}{237,4} \cdot \frac{141,1}{198,1} \right) \cdot \frac{141,1}{141,1} = 0,1045 ;$$

Settlement factor for loss of power during transfer:

$$0,1046 - 0,1045 = 0,0001 .$$

Calculations of settlement factors for path from generator node 5 to load node 11:

Settlement factor for the transmitted power from generator node 5:

$$\left(\frac{325,5}{325,5} \cdot \frac{223,1}{324,9} \right) \cdot \frac{67}{543,3} = 0,0847 ;$$

Settlement factor for received power in load node 11:

$$\left(\frac{324,9}{325,5} \cdot \frac{222,1}{324,9} \right) \cdot \frac{67}{543,3} = 0,0841 ;$$

Settlement factor for loss of power during transfer:

$$0,0847 - 0,0841 = 0,0006$$

Calculations of settlement factors for path from generator node 5 to load node 12:

Settlement factor for the transmitted power from generator node 5:

$$\left(\frac{325,5}{325,5} \cdot \frac{223,1}{324,9} \cdot \frac{236,2}{543,3} \right) \cdot \frac{234,7}{234,7} = 0,2985 ;$$

Settlement factor for received power in load node 12:

$$\left(\frac{324,9}{325,5} \cdot \frac{222,1}{324,9} \cdot \frac{234,7}{543,3} \right) \cdot \frac{234,7}{234,7} = 0,2948 ;$$

Settlement factor for loss of power during transfer:

$$0,2985 - 0,2948 = 0,0037 .$$

Table 2 presents settlement factors of supplies from the generator to the load nodes. 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.

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}	$A_{f5i}P_5$	A_{f8i}	$A_{f8i}P_8$	A_{f13i}	$A_{f13i}P_{13}$	A_{f14i}	$A_{f14i}P_{14}$	A_{f17i}	$A_{f17i}P_{17}$	A_{f18i}	$A_{f18i}P_{18}$	
1 transm. received losses	0,1046	17,27	0,0177	2,03	0,0177	2,54	0,0192	11,84	0,0037	0,64			34,31
	0,1045	17,24	0,0174	2,00	0,0175	2,51	0,0190	11,69	0,0036	0,62			34,06
	0,0001	0,03	0,0003	0,03	0,0002	0,03	0,0002	0,14	0,0001	0,01			0,25
2 transm. received losses	0,0721	11,89	0,0479	5,50	0,0479	6,88	0,0521	32,03	0,0099	1,72			58,02
	0,0703	11,60	0,0466	5,34	0,0467	6,71	0,0508	31,24	0,0096	1,67			56,56
	0,0018	0,29	0,0013	0,15	0,0012	0,17	0,0013	0,80	0,0003	0,05			1,46
3 transm. received losses	0,1829	30,18	0,1216	13,94	0,1216	17,46	0,1322	81,29	0,0251	4,36			147,23
	0,1772	29,24	0,1174	13,47	0,1177	16,90	0,1273	78,29	0,0241	4,20			142,09
	0,0057	0,94	0,0042	0,48	0,0039	0,56	0,0049	3,00	0,0009	0,16			5,14
4 transm. received losses			0,0984	11,29	0,0984	14,13	0,1070	65,81	0,0203	3,53			94,76
			0,0971	11,13	0,0973	13,97	0,1058	65,07	0,0200	3,47			93,64
			0,0014	0,16	0,0011	0,16	0,0012	0,74	0,0003	0,06			1,12
6 transm. received losses	0,2087	34,43	0,0353	4,05	0,0353	5,07	0,0384	23,61	0,0073	1,27			68,43
	0,2083	34,37	0,0348	3,99	0,0349	5,01	0,0379	23,32	0,0072	1,24			67,93
	0,0004	0,06	0,0005	0,06	0,0004	0,06	0,0005	0,29	0,0001	0,02			0,50
7 transm. received losses	0,0485	8,00	0,0322	3,70	0,0322	4,63	0,0350	21,55	0,0066	1,16			39,04
	0,0477	7,87	0,0316	3,63	0,0317	4,55	0,0345	21,20	0,0065	1,13			38,38
	0,0008	0,13	0,0006	0,07	0,0005	0,08	0,0006	0,36	0,0001	0,03			0,66
9 transm. received losses			0,3921	44,97	0,3921	56,31	0,0406	24,95	0,0077	1,34			127,57
			0,3900	44,74	0,3910	56,15	0,0405	24,88	0,0076	1,33			127,09
			0,0021	0,24	0,0011	0,16	0,0001	0,07	0,0001	0,01			0,48
11 transm. received losses	0,0847	13,97	0,0563	6,46	0,0563	8,08	0,0612	37,64	0,0116	2,02			68,17
	0,0841	13,88	0,0552	6,33	0,0553	7,95	0,0602	37,02	0,0114	1,97			67,16
	0,0006	0,09	0,0011	0,12	0,0009	0,14	0,0010	0,62	0,0003	0,04			1,01
12 transm. received losses	0,2985	49,26	0,1984	22,76	0,1984	28,50	0,2157	132,68	0,0409	7,12			240,32
	0,2948	48,64	0,1934	22,18	0,1939	27,84	0,2108	129,67	0,0398	6,92			235,24
	0,0037	0,62	0,0050	0,58	0,0046	0,66	0,0049	3,02	0,0012	0,20			5,08
15 transm. received losses							0,2985	183,59	0,0566	9,85			193,44
							0,2953	181,59	0,0557	9,69			191,28
							0,0033	2,00	0,0009	0,16			2,16
16 transm. received losses									0,2950	51,30			51,30
									0,2933	51,00			51,00
									0,0017	0,30			0,30
19 transm. received losses									0,0744	12,94	1,0000	35,3	48,24
									0,0736	12,80	0,9972	35,2	48,00
									0,0008	0,14	0,0028	0,1	0,24
21 transm. received losses									0,4409	76,66			76,66
									0,4393	76,40			76,40
									0,0015	0,26			0,26

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 consider 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

Distribution of active and reactive power between consumers raises the problem of participation of each power station in supply of loads and determining flows of power from each generator through branches of an electric power network. Interest of this problem mainly is chosen by the development of open access market in power systems. In this paper a method was reviewed of determination of settlement factors, which is based on finding the trace in oriented graph, and allows, with the number of cycles equal with the number of generator nodes, determine the part of active power, which flow from each generator through branches of electric network to load node.

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 prospectively of settlement algorithms in conditions of developing financially – economic relations between participants of power market.

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