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Cost Allocation for Transmission System using Distribution Factor

T.Rajamanikandan[1], Mohanraj K[2] and Karthik.K[3]
[1-3]Assistant professor Kongunadu college of engineering and technology,Tholurpatty Thottiyam, India
mvtbharatham@gmail.com, mohan.kabilan@gmail.com, karthick.ks24@gmail.com

***Abstract*— One of the key problems of energy transmission system in an independent environment refers to necessity to establish a cost for system services on nondiscriminatory bases. The prices must to be simple and transparent. A properly established cost provides economical signals for short-term and long-term recovery current expenses and for a fair cost allocation for participants. This paper presents allocation of transmission costs to consumers and to generator using the distribution factors method. A detailed comparison between regime with active losses and the regime without active losses are presented. A case study based on a 12-node system is provided.**

I. INTRODUCTION

The transmission cost is the most complicated issues in power system restructuring, because of physical laws, which governs the transmission network power flow. Since generators and consumers are connected to the transmission network, a participants action has consequences to other participants too, making difficultly the investigation of components price, which cost one to each participant Transmission active loss allocation is the process of assigning to each individual generation and load the responsibility of paying for a part of the system transmission active losses. Transmission active loss allocation is not an easy task. Loss allocation between the generator and the load has to be agreed upon as there is no physical measurement or mathematical method that determines the loss shares in a unique manner. In a real system, matters get more complicated because of nonlinear function of the line power flow, and hence cannot be separated between partial flows through the same line in a unique convincing way. In this paper an analysis of the allocation method using distribution factors is proposed. The distribution factors method was extended to calculate the AC power flow, heaving the object the calculus of the system cost allocation for the regime with active power losses. The distribution factors are the relative change of power flow on a network element, causing by the change of power generated and / or those consumed. Generally speaking, they depend on the power system topology, the operating system and the direction of power flow. The There are three categories of factors [IO]:

- Generation Shift factors (A factors), which provide line flow changes due to a change in generation (without changing of overall of system power balance). They depend on the selection of reference bus, but are independent of the system
- Generalized Generation Distribution Factors (D factors) determine the impact of each generator on active power flow through network elements. They depend on network elements and operating regime and not on the choice of reference bus.

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- Generalized Load Distribution Factors (C factors) reflect the participation of each consumer to active power flow through networks elements. They depend on network elements and operating regime and not on the choice of reference bus.

II. PRESENTATION OF DISTRIBUTION FACTORS METHOD

Generatio Shift factors (A factors) [II] are defined as:

$$\Delta P_{e,jk} = A_{jk,i} \cdot \Delta P_{gi} ,\ jk \in R ,\ i \in N \backslash e$$

$$\Delta P_{ge} + \Delta P_{gi} = 0 \qquad (1)$$

Where: *jk* - change in active power through network ele- ment jk; *Ajk,i* - generation shift factors through network element *jk,* Corresponding to change in generator at bus i; *DPgi* – change In generation at bus i (i e) , *DPge* - change in generation at Slack bus. The A factors are determined by DC power flow (which means the neglecting of longitudinal resistance, transversal susceptances and conductances of network elements, neglecting reactive power flow and considering all voltages equal to unity).

$$\mathbf{P} = -\mathbf{B}^{-1}\mathbf{s} \qquad (2)$$

Where: P - vector of injected power in system buses; 6 – vector of nodal voltage angles; B - nodal susceptance matrix. The voltage angles result:

$$d - -\mathbf{B}^{-1}.\ \mathbf{P} \qquad (3)$$

Which means (with b, j e N, i e N - B 1 matrix elements):
With same conditions, the relation (2) becomes:

$$Pl - -Bl\ '\ 6l \qquad (5)$$

Where: Pl - vector of active power through network elements; s vector of difference of voltage angles from ends of network element jk; Bl - diagonal matrix of longitudinal susceptances of network element *jk.*
Writing in extended variant the relation (5) lead to:

$$PtJk\_\_\_Bl\ jk\ '(dj - dk),\ jk\ e\ R \qquad (6)$$

Using the relation (, relation (6) becomes:

$$\mathbf{Pl}\ jk\ = Bl\ jk\ .|\sum_{Li\ eN} (b\ jil-\ '\ Pi) - \sum_{ieN\_\backslash} (b\ '\ Pi)| = \qquad (7)$$

$$= Bl\ jk\ '\sim\ NS[(b\ j\text{-}il - bki\text{-}I)'\ Pi\ ,jk –$$

Relation (7) is linear and the modification of power through network element, *DPl jk* , due the injected power in bus i, Dpi Can be expressed:

$$\Delta \mathbf{PE}\ jk\_\_Bl\ jk\ '\ (b\ jil\text{-}\ \underline{bkil}\text{-}).\Delta \mathbf{pi} \qquad (8)$$

Comparing the relations (8) and (I), the expression of a factors for network element *jk,* corresponding to the change of generated power in bus i:

$$A]''k,\ i - Bl\ jk.\ (b\ ji^{-1} – bki^{-1}),\ jk \in R ,\ i \in N \backslash e \qquad (9)$$

Generalized generation distribution factors (D factors) [II] determine the impact of each generator on active power flow on network elements (so, they can have negative values). They are determined in conditions of DC power flow too, being defined by the relation:

$$Pt,jk = \sum_{i \in N} (D\ jk,i\ '\ Pgi)\ ,\ jk \in R \qquad (10)$$

Where: Pl, jk - active power flow through network element *jk; Pg!* - generated power in bus i; *Djk,i* - D factor of the network element *jk,* corresponding to the generated power in bus i:

$$D_{jk,i} = D_{jk,e} + A_{jk,i} = \frac{P^0_{jk} - \sum_{i \in N \backslash e} (A_{jk,i} \cdot P_{gi})}{\sum_{i \in N} P_{gi}} + A_{jk,i} \qquad (11)$$

Where: Pj - power flow through network element *jk* from The previous iteration; e - the slack bus.D factors reflect the utilization rate of electricity transmission capacity epending on generated power (unlike the A factors, which indicated the incremental rate of use). They depend on network elements and operating regime and not on the choice of reference bus.

Generalized load distribution factors (C factors) [II] are very similar to D factors and determine the contribution of each load to network elements (so, they can have negative values). They are determined in conditions of DC power flow too, being defined by the relation:

$$\text{Pt, jk}=\sum_{\text{ieN}} (Cjk, Pct)\ j.\ €R \quad (12)$$

Where: Pl, jk - active power flow through network element *jk; Pct* - power consumed in bus i; *Cjk, i* - C factor of the network Element *jk,* corresponding to power generated in bus i: (7)

$$D_{jk,i} = D_{jk,e} + A_{jk,i} = \frac{P^{0}_{jk} - \sum\limits_{i \in N \setminus e} (A_{jk,i} \cdot P_{gi})}{\sum\limits_{i \in N} P_{gi}} + A_{jk,i}$$

Where PQk - power flow through iEnNetWork element *jk* from the previous iteration. C factors reflect the utilization rate of electricity ransmission capacity depending on consumed power. They depend on network elements and operating regime and not on the choice of reference bus [11].

III. CASE STUDY

The test system with 12 buses is shown in Fig. I. Bus I am the slack bus. The network elements parameters are presented in Table I. Table 2 contains the initial data of buses and the results of power flow for considered operating regime. Table 3presents the power flows through network elements.

TABLE I. NETWORK ELEMENTS P~TERS

Bus i	Bus j	R [p.u.}	X [p.u.}	B [p.u.}	L [km}	Bus i	Bus j	R [p.u.}	X [p.u.}	B [p.u.}	L [km}
1	2	0.00415	0.02500	0.04000	30	6	5	0.00554	0.03335	0.05379	40
1	6	0.00969	0.05838	0.09490	70	6	9	0.00415	0.02500	0.04000	30
1	7	0.01660	0.10000	0.16132	120	6	11	0.00692	0.04170	0.06725	50
2	8	0.00415	0.02500	0.04000	30	10	7	0.00554	0.03335	0.05379	40
3	7	0.00526	0.03169	0.05110	38	9	10	0.00277	0.01667	0.02690	20
8	3	0.00623	0.03752	0.06000	45	10	11	0.00692	0.04170	0.06725	50
5	4	0.00830	0.05000	0.08000	60	10	12	0.00484	0.02912	0.04700	34
7	4	0.00387	0.02335	0.03765	28	11	12	0.00346	0.02080	0.03360	25
11	4	0.00830	0.05000	0.08000	60						

TABLE II. DATES AND RESULTS FOR BUSES

Bus	U [kV}	d [grd}	Pc [MW"}	Qc [MVar}	Pg [}	Qg [MVAB}
1	**231.000**	**0.00**			**490.89**	**285.76**
2	220.000	1.68	300.00	35.00	340.49	122.84
3	220.000	-2.08			350.00	13.37
4	220.000	-4.28			293.72	41.82
5	220.000	-2.61	350.00	25.00	600.00	15.82
6	220.000	6.39	230.00	60.00	200.00	126.57

Bus	U [kV]	δ [grd]	P_C [MW]	Q_C [MVar]	P_g [MW]	Q_g [MVAR]
7	217.587	-6.48	350.00	38.00		
8	217.440	-4.42	300.00	25.00		
9	215.443	-9.69	208.00	30.00		
10	214.946	-9.91	170.00	20.00		
11	215.467	-9.55	210.00	23.00		
12	214.322	-10.64	130.00	15.00		

TABLE III. POWER FLOW RESULTS FOR NETWORK ELEMENTS

Bus	Bs j	Pij [MW}	Qij [Mvar}	SI.n. ax *fl* [MVA}	AP [MW}	AQ [MVAB }
1	2	154.1	184.0	100.0	2.22	9.04
1	6	211.3	60.8	91.6	4.34	15.97
1	7	125.5	40.9	55.0	2.81	-0.25
2	8	192.3	17.1	80.5	1.57	5.39
3	7	240.0	1.4	100.0	3.05	13.20
8	3	109.2	13.3	46.1	0.79	1.31
5	4	56.6	12.5	24.1	0.30	6.36
7	4	165.6	17.7	70.0	1.11	2.88
11	4	180.4	5.9	76.6	2.85	9.14

Bus i	Bus j	P_{ij} [MW]	Q_{ij} [Mvar]	S_{ij}^{max} [MVA]	ΔP [MW]	ΔQ [MVAR]
6	5	-191.3	35.6	81.4	2.13	7.31
6	9	233.8	48.5	99.5	2.38	10.39
6	11	134.4	27.3	57.2	1.34	1.34
10	7	-173.5	-3.7	73.1	1.77	5.32
9	10	23.4	8.1	10.7	0.03	-2.46
10	11	-14.9	-6.2	6.7	0.04	-6.33
10	12	41.8	0.6	17.5	0.11	-3.94
11	12	88.6	9.0	37.1	0.30	-1.48

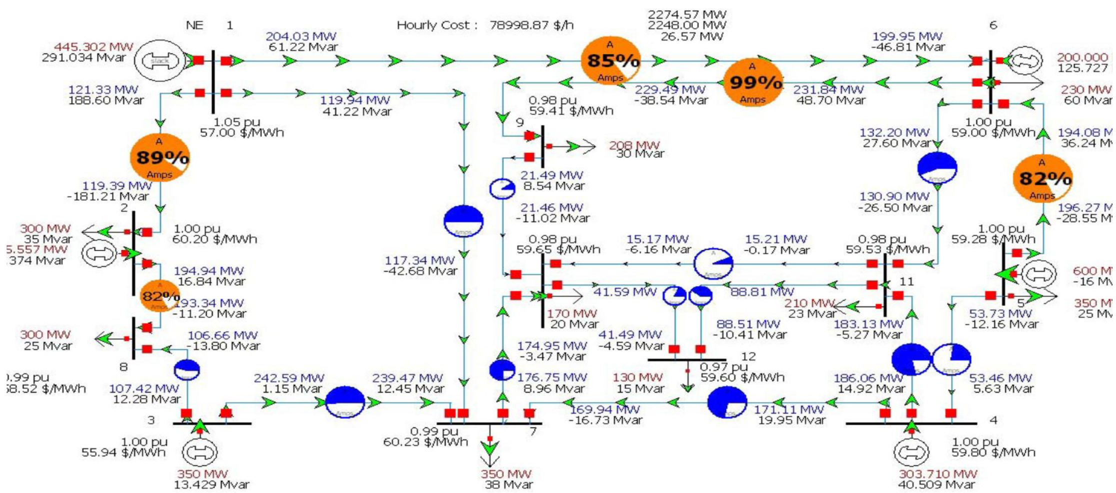

Fig. I. Test system with 12 brises, normal operation regime [11]

For the calculation we used Mathematica @ environment, application software DFPQ (Distribution Factor for Active and Reactive Power) being developed by the author [11]. fhe obtained components of the power vector P injected the buses (except slack bus), are given the table [V]. fhe nodal susceptance matrix B is given below.

TABLE IV. ACTIVE POWER FLOW THROUGH NETWORK ELES

Bus	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Pi	***418.7***	***75.6***	***350***	***303.7***	***250***	***-30***	***350***	***300***	***-208***	***170***	***-210***	***130***

B=

122.736	-73.1613	0	0	0	-31.3562	-18.2183	0	0	0	0	0
-73.1613	142.647	0	0	0	0	0	-69.4853	0	0	0	0
0	0	101.067	0	0	0	954.8165	-46.25	0	0	0	0
0	0	0	143.882	-34.8701	0	-74.5259	0	0	0	-34.486	0
0	0	0	-34.8701	87.2435	-52~3733	0	0	0	0	0	0
-31~3562	0	0	0	-52.3733	193.891	0	0	-68~8554	0	-41~3057	0
-18.2183	0	-54~8165	-74.5259	0	0	198.968	0	0	-51~4076	0	0
0	-69.4853	-46.25	0	0	0	0	115.735	0	0	0	0
0	0	0	0	0	-68~8554	0	0	171.355	-102.5	0	0
0	0	0	0	0	0	-51~4076	0	-102.5	253.434	F40~5263	-59~
0	0	0	-34.486	0	-41.3057	0	0	0	-40.5263	198.448	-82.1296
0	0	0	0	0	0	0	0	0	-59.	-82.1296	141.13

From nodal susceptance matrix is removed the line I and column I, corresponding to slack bus (de - 0) and the matrix Obtained is inversed, resulting B -/ using the relation (4), The values of voltage angles are calculated, resulting finally, based on relation, the power flow through network elements.

TABLE V. ACTIVE POWER FLOW THROUGH

No.	Bus j	Bus k	Pl *jk* [MW'[	*Plkj* [MW'[
1	1	2	113.4	113.4
2	1	6	191.9	191.9
3	1	7	113.5	113.5
4	2	8	189.0	189.0
5	3	7	239.0	-239.0
6	3	8	111.0	111.0
7	4	5	-53.7	53.7
8	4	7	172.9	172.9
9	4	11	184.5	184.5

No.	Bus *j*	Bus *k*	$P_{\ell jk}$ [MW]	$P_{\ell kj}$ [MW]
10	5	6	196.4	-196.4
11	6	9	228.6	-228.6
12	6	11	129.7	-129.7
13	7	10	175.3	-175.3
14	9	10	20.5	-20.5
15	10	11	-15.4	15.4
16	10	12	41.3	-41.3
17	11	12	88.7	-88.7

Then, the longitudinal susceptance matrix of network elements Applying relation (9), we can calculate the A Distributio Bl is built. Factors.

A=

-0.855434	-0.474534	-0.246909	-0.202962	-0.173702	-0.281587	-0.281587	-0.703219	-0.204932	-00.225911	-0.216403	mO.220378
-0.0744469	-0.270597	-0.44755	~0.54588	-0.611349	-0.369958	-0.369958	-0.152832	0.541472	90.494531	-O.S1S806	-0.506912
-0~0701196	-0.254869	-0.305541	-0.251158	-0.21495	-0.348454	-0.348454	-0.143949	F 0.253596	-0.279557	-0.267791	-0.27271
0.144566	-0.474534	-0~246909	-0.202962	-0.173702	-0.281587	-0.281587	-0.703219	-0.204932	-0.225911	90.216403	-0.220378
-0.0259832	-0.094442	0.413567	0.246727	0.135646	-0.129121	-0.129121	-0.0533409	0.0950113	0.0677147	0.165509	0.124626
-0.288463	8	0~804168	0.582375	0.434706	0.410227	0.410227	~0.592187	0.458001	0.473651	0.538632	0.511466
0.020946	-0.048497	0~21022	-0.381309	-0.109349	0.10409	0.10409	0.0430002	-0.0338127	0.0169297	0.026553	0.0225299
-0.0353255	5	0.562265	0.335438	0.184417	-0.175547	-0.175547	~0.0725197	;)2909336	0.0920617	0.225018	0.169435
0,0143794	0.076134	0.227515	0.0458705	-0.075068	0.0714574	0.0714574	0.0295195		-0.108991	-0.251571	-0.191965
0.020946	-0.1284	0.21022	0.618691	-0.109349	0.10409	0.10409	0.0430002	0.0338127	0.0169297	0.026553	0 0225299
~0.0293923	0.0522658	-~O.0950216	0.0541348	0.153443	-0.146063	-0.146063	-0.0603395	0.527787	-0.31365	90.135537	-0~209998
-0.0241085	0.076134	-0.142308	0.0186759	0.125859	-0.119806	-0.119806	-0.0494925	0.0474973	-0.163951	-0.353716	-0.274384
0"0391214	-0.106834	0.00981545	~0.118681	-O.Zo4Z34	0.194411	0.194411	0.0803125	0.329355	-0.413407	~0.259176	-0.323653
-0.0293923	-0.087629	-0.09S0216	0.0541348	0.153443	-0.146063	-0.146063	-0.0603395	0.472213	90.31365	-0.135537	-0~209998
0.0052669	0.142197	-0.0461267	-0.0349424	-0.027496	0.0261735	0.0261735	0.0108124	0.0773364	0.147759	-0.21368	-0.0625784
0~00446223	-0.106834	-0.0390795	~O.029604	-0.02329S2	0.0221747	0.0221747	0.00916052	O.065521	0.125184	-0.181034	-0~471073
~0.0044622	0.019144	0.0390795	0.029604	0.0232952	-0.0221747	-0.0221747	~0.00916052	-O.O6SS21	-0.125184	0.181034	-0.SZ8927

The D distribution factors matrix is the following:

D=

0.370221	-0.485213	-0.104314	0.123312	0.167259	0.196519
0.400484	0.326037	0.129887	-0.0470666	-0.145397	-0.210865
0.229322	0.159203	-0.0255465	-0.0762186	-0.0218357	0.0143725
0.236787	0.381354	-0.237747	-0.0101217	0.0338253	0.0630853
-0.0084326	-0.0344158	-0.102875	0.405134	0.238295	0.127213
-0.197637	-0.486101	-0.246135	0.60653	0.384738	0.237068
0.0438591	0.0648051	0.119993	0.25408	-0.33745	-0.0654902
-0.0790945	-0.11442	-0.207494	0.483171	0.256344	0.105323
0.0352309	0.0496103	0.0874968	0.262745	0.0811014	-0.0398371
-0.11179	-0.0908436	-0.0356556	0.0984308	0.506901	-0.221139
0.107971	0.0785788	0.00113693	0.0129495	0.162106	0.261414
0.0784104	0.0543019	-0.00921852	-0.063898	0.0970863	0.20427
0.0978256	0.136947	0.240023	0.107641	-0.0208556	-0.106409
0.0154003	-0.013992	-0.0914338	-0.0796213	0.0695351	0.168843
0.00729328	0.0125602	0.0264372	-0.0388334	-0.0276492	-0.0202027
0.0303547	0.0348169	0.0465739	-0.00872476	0.000750754	0.00705954
0.0274742	0.023012	0.011255	0.0665537	0.0570782	0.0507694

Using the relation (13) we will be determine the C distribution These factors are calculated only for consumer buses 7, factors (Table VI). 8, 9, 10, II and 12.

After that it goes on to present the allocation of electricity Total transmission cost was calculated based on unit cost transmission costs to energy market participants - in om case, and on the active power flow (Table IV), results being presented for producers and consumers. It is considered as a basis for in Table 7. Calculating a unit cost of transport lines 2 $/MW'km.

Using D distribution factors, there is determining the transmission factors, it determines the transmission costs allocated to costs allocated to generators (Table VIII). Using C distribution consumers (Table IX).

TABLE VI. THE C DISTRII3UTION FACTORS

NETWORK	CJK7	CIKS	CJK9	CJK10	CJK11	CJK12
I-2	-0.140961	0.280671	-0.217616	0.196637	-0.206145	0.202170
I-6	-0.169625	0.386751	0.001889	-0.0450514	-0.023777	0.032671
I-7	0.004445	0.200061	-0.090413	-0.0644521	-0.076218	0.071299
2-8	-0.196224	0.225408	-0.272879	0.251900	-0.261408	0.257433
3-7	-0.030208	0.105989	-0.254341	0.227044	-0.324838	0.283955
3-8	-0.256490	0.745924	-0.304265	0.319914	-0.384895	0.357730
4-5	-0.025595	0.035495	0.112308	0.061565	0.051942	0.055965
4-7	0.070066	0.032962	-0.234654	0.197543	-0.330500	0.274916
4-1l	-0.266474	0.224536	-0.099657	0.086025	0.056554	0.003052
5-6	-0.208416	0.147327	-0.070514	0.121256	-0.130879	0.126856
6-9	-0.231632	0.317355	0.150092	0.064045	-0.242158	0.167697
6-II	-0.124479	0.194792	-0.196787	0.080333	0.109431	0.030099
7-10	-0.427196	0.313097	0.096571	0.180622	0.026392	0.090868
9-10	0.072534	0.013189	-0.545741	0.240122	0.062009	0.136470
10-II	-0.014476	0.000885	-0.065639	0.136062	0.225377	0.074275
10-12	-0.091720	0.078706	-0.135066	0.194729	0.111489	0.401528
1l-12	-0.098339	0.111353	-0.054992	0.004671	-0.301547	0.408413

TABLE VII. THE TOTAL FNERGY

Bus	Bus j	Unit transmission cost [$/MW}	P... ~y	Total transmission cost [$}		Bus	Bus j	Unit transmission cost [$/MW}	P... ~y	Total transmission cost [$}
I	2	60	113.4	6804		5	6	80	196.4	15712
I	6	140	191.9	26866		6	9	60	228.6	13716
I	7	240	113.5	27240		6	1l	100	129.7	12970
2	8	60	189	11340		7	10	80	175.3	14024
3	7	76	239	18164		9	10	40	20.5	820
3	8	90	111	9990		1l	10	100	15.4	1540
5	4	120	53.7	6444		10	12	68	41.3	2808.4
4	7	56	172.9	9682.4		1l	12	50	88.7	4435
4	II	120	184.5	22140						
Total										204695.8

TABLE VIII. TRANSMISSION COSTS ALLOCATED TO GFNERATORS

COST ALLOCATED TO GENERATOR 1 [$]	COST ALLOCATED TO GENERATOR 2 [$]	OST ALLOCATED TO GENERATOR 3 [$]	COST ALLOCATED TO GENERATOR 4 [$]	COST ALLOCATED TO GENERATOR 5 [$]	OST ALLOCATED TO GENERATOR 6 [$]	TOTAL COST [$]
82945.7	9367.1	44195.8	28765.4	39421.8	1832.5	204695.8

TABLE IX. TRANSMISSION COSTS ALLOCATED TO CONSUMERS

COST ALLOCATED TO CONSUMER 7 [$]	*COST ALLOCATED TO CONSUMER 8 [$]*	*COST ALLOCATED TO CONSUMER 9 [$]*	*COST ALLOCATED TO CONSUMER 10 [$]*	*COST ALLOCATED TO CONSUMER 11 [$]*	*COST ALLOCATED TO CONSUMER 12 [$]*	*TOTAL COST [$]*
51787.5	29878.9	36137.7	23103.0	38105.1	25683.7	204695.8

Obviously, costs allocation was done separately for sources can be weighted differently (in the range 0-: I, their sum is (sources share I, consumers share 0) and consumer (consumer obviously I). Share I, sources share 0), identifying active power tracing for losses regime it obtained the following results for Cost flow. The two components of the transmission cost allocation allocated to generators (Table X and Table XI):

TABLE X. TRANSMISSION COSTS ALLOCATED TO GENERATORS (REGIME WITH LOSSES)

COST ALLOCATED TO GENERATOR 1 [$1	OST ALLOCATED TO GENERATOR 2 [$1	COST ALLOCATED TO GENERATOR 3 [$1	COST ALLOCATED TO GENERATOR 4 [$1	OST ALLOCATED TO GENERATOR 5 [$1	COST ALLOCATED TO GENERATOR 6 [$1	TOTAL COST [$1
85001.3	9367.1	44195.8	28765.4	39421.8	1832.5	208583.9

TABLE XI. TRANSMISSION COSTS ALLOCATED TO CONSUMERS (REGIME WITH LOSSES)

COST ALLOCATED TO CONSUMER 7 [$1	OST ALLOCATED TO CONSUMER 8 [$1	COST ALLOCATED TO CONSUMER 9 [$1	COST ALLOCATED TO CONSUMER 10 [$1	COST ALLOCATED TO CONSUMER 11 [$1	COST ALLOCATED TO CONSUMER 12 [$1	TOTAL COST [$1
52771.1	30446.4	36824.1	23541.9	38828.8	26171.5	208583.8

IV. CONCLUSION

This paper presents allocation of transmission costs using an extended version of distribution factors methods. The proposed method takes losses into consideration during the calculus process based on the following hypothesis very realistic, especially if one takes into account the lowest share of losses in power flow through network elements. It is considered only change of active power generated in slack bus, distribution factors remaining unchanged Regarding the method of distribution factors, applied to 12 nodes test system, it is notable difference of generators and consumers transmission costs allocation, between the cases without and with active power losses. The recommendation is clear: do not neglect the active power losses.

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