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Transmission Cost Allocation Using Distribution Factors for AC Power Flow

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Abstract

This paper goal to analyze the costs that are associated with the power transfer as well as the designing of new computer techniques and the allocation of these costs based on AC power flow method vs. DC power flow method. IEEE-12 bus system results are analyzed the Method based on AC power flow using distribution factors.

1. INTRODUCTION

The transmission cost allocation is the most complicated problem in power system, that because of physical laws. The generators and consumers are connected to the transmission network, participant's action consequences to other too.

In this paper an analysis of the cost allocation method using distribution factors is proposed. This method extended to calculate AC power flow. The factors are relative change of power flow on a network element, because of the change of power generated/consumed.

The distribution factors are used the regime, contingency analysis and safe operation, which reflecting the impact of the generated/consumed power of electrical energy.

2. DISTRIBUTION FACTORS METHOD

***A factors** (Generation shift factors)* *defined as follows*

$$\Delta P_{l,jk} = A_{jk,i} . \Delta P_{gi} \quad \text{-- (1.1)}$$

$$\Delta P_{ge} + \Delta P_{gi} = 0 \quad , jk \in R, i \in N \backslash e \text{ \_(1.2)}$$

Where:

$\Delta P_{l,jk}$ - Change in active power through the element jk in network.

$A_{jk,i}$ - Generation shift factors through network element jk, corresponding to the change at bus i.

ΔP_{ge} -change in generation at slack bus.

ΔP_{gi} - change in generation at bus i (i≠e).

GSD's (A factors) determined by DC power flow

P = - B.δ ---- (2.0)

Where:

P – Vector of injected power in system buses;

δ –vector of nodal voltage angles;

B- Nodal susceptance matrix.

Voltage angle results:

$$\delta = -B^{-}.P \quad \text{---- (3.0)}$$

Which means (noting with b_{ji}^{-1} ,j ϵ N, i ϵ N, the elements of B^{-}) :

$$\delta_j = -\sum_{i \in N} b_{ji}^{-1}.P_i \quad , j \in N \text{ --- (4.0)}$$

Hence the relation (2.0) becomes:

$$P_l = -B_l.\delta_l \quad \text{--- (5.0)}$$

Where

P_l - Vector of power through elements of the network

B_l - Diagonal matrix of longitudinal susceptances of network elements jk.

δ_l -vector of difference of voltage angles from ends of network elements jk ;

Writing in extended the relation **(5.0)** lead to:

$$P_{l,jk} = -B_{l,jk}(\delta_j - \delta_k),\ jk \in R \quad \text{-- (6.0)}$$

Using the relation **(4.0),** relation **(6.0)** becomes:

$$P_{l,jk} = B_{l,jk}\left[\sum_{i\in N}(b_{ji}^{-1}.P_i) - \sum_{i\in N}(b_{ki}^{-1}.P_i)\right] = B_{l,jk}.\sum_{i\in N}[(b_{ji}^{-1} - b_{ki}^{-1}).P_i],\ jk \in R \quad \text{--- (7.0)}$$

Equation **(7.0)** is linear and the modification of power through network element, $\Delta P_{l,jk}$,due to changing of power injected in bus I , ΔPi can be expressed as :

$$\Delta P_{l,jk} = B_{l,jk}(b_{ji}^{-1} - b_{kl}^{-1}).\Delta P_i \quad \text{---- (8.0)}$$

By comparing the equations **(8.0)** and **(1.0),** the expression of A factors for network element jk , corresponding changing of generated power in bus i:

$$A_{jk,i} = B_{l,jk}(b_{ji}^{-1} - b_{kl}^{-1}),\ jk \in R,\ i\in N\backslash e \quad \text{------ (9.0)}$$

D factors (Generalized generation distribution factors) determines the impact of each generator on active power flow on network elements (they can have negative values).

They determined in conditions of DC power flow too, being defined by the relation:

$$P_{l,jk} = \sum_{i\in N}(D_{jk,i}.P_{gi}),\ jk \in R \quad \text{--- (10.0)}$$

Where

$P_{l,jk}$ - Active power flow

P_{gi} -power generated in bus i

$D_{jk,i}$ - D factor of a network elements jk, corresponding to power generated in bus i:

$$D_{jk,i} = D_{jk,e} + A_{jk,i} = \frac{P_{jk}^0 - \sum_{i\in N\backslash e}(A_{jk,i}.P_{gi})}{\sum_{i\in N}P_{gi}} + A_{jk,i} \quad \text{---- (11.0)}$$

Where P_{jk}^0 - power flow on network elements jk from the previous iteration.

e- Slack bus.

D factors reflect the utilization rate of electricity transmission capacity depends upon the generated power and they depend on network elements and operating regime and not on the choice of reference bus.

C FACTORS (Generalized load distribution factors) are similar to D Factors.

They are determined in conditions of DC power flow too, defining by the following relation:

$$P_{l,jk} = \sum_{i\in N}(C_{jk,i}.P_{ci}),\ jk \in R \quad \text{--- (12.0)}$$

Where

$P_{l,jk}$ – Active power flow on network elements jk;

P_{ci} – Power consumed in bus i;

$C_{jk,i}$ – C factor of a network element jk, corresponding to power generated in bus i;

$$C_{jk,i} = C_{jk,e} - A_{jk,i} = \frac{P_{jk}^0 - \sum_{i\in N\backslash e}(A_{jk,i}.P_{ci})}{\sum_{i\in N}P_{ci}} - A_{jk,i} \quad \text{--- (13.0)}$$

Where P_{jk}^0 - power flow on network elements jk from the previous iteration.

e- Slack bus.

C factors reflect the utilization rate of electricity transmission capacity depends upon the consumed power and they depend on network elements and operating regime and not on the choice of reference bus.

3. CASE STUDY

The test system is shown in figure 1.0. Bus 1 is the slack bus.

And the network element parameters showed in the tabular column 1.0.

Tabular column 2.0 re-presents the initial data of buses and the results of power flow for considered operating regime.

Tabular column 3.0 represents the results of the power flow for line system. The computing method DFPQ (distribution factor for active and reactive power), has been developed in mathematical environment.

The components of the power vector P injected into the system buses (except slack bus) has been determined and shown in the tabular column (1.0)

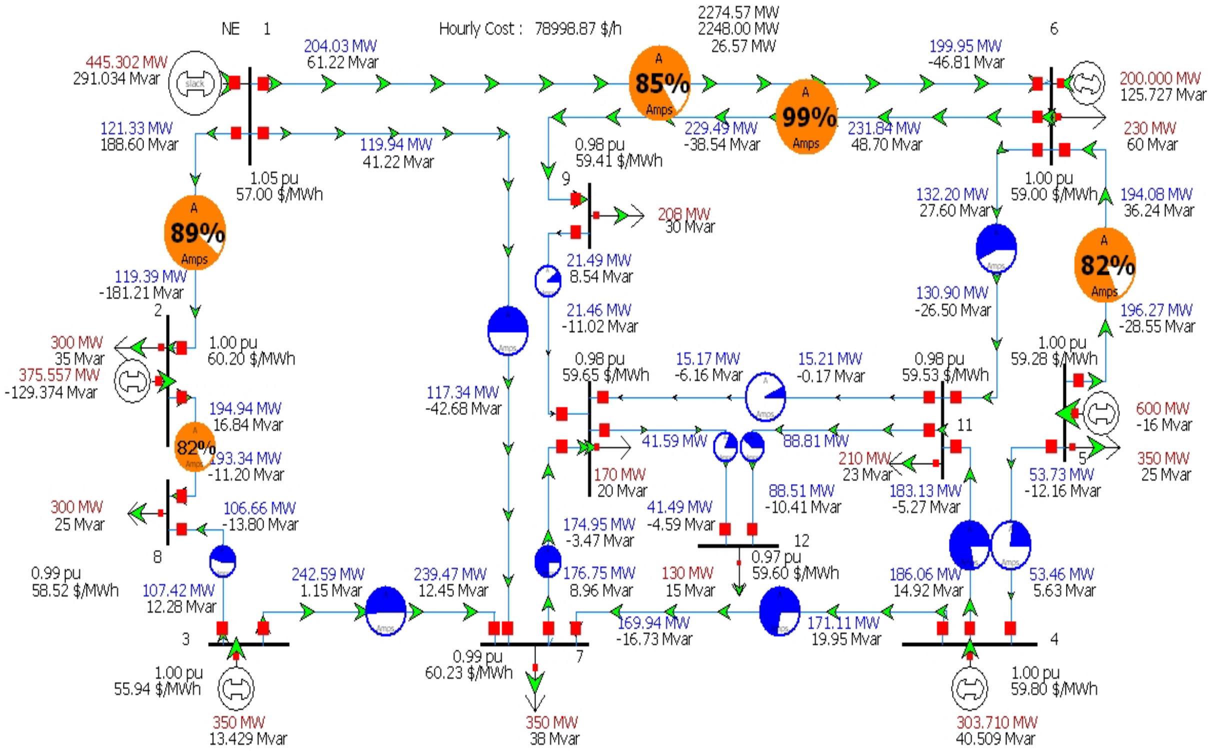

Fig 1.0 Test system with 12 buses, normal operating regime

Table 1.0 Networks Elements Parameter

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

Table 2.0 Bus power flow results

Bus	U(kV)	δ(grd)	Pc(MW)	Qc(MVar)	Pg (MW)	Qg(MVAR)
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	13.370
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
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	215.946	-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 3.0 Power flow results for network elements

Bus i	Bus j	Pij (MW)	Qij (MVar)	S_{ij}^{max} (MVA)	ΔP(MW)	ΔQ(MVAR)
1	2	154.2	184.1	100.1	2.25	9.09
1	6	211.4	60.9	91.7	4.36	15.99
1	7	125.6	40.8	55.1	2.85	-0.27
2	8	192.4	17.1	80.5	1.56	5.38
3	7	240.0	1.4	100.0	3.08	13.23
8	3	-109.2	-13.3	46.1	0.78	-1.35
5	4	56.6	-12.5	24.1	0.36	-6.37
7	4	-165.6	-17.7	70.0	1.16	2.89
11	4	-180.4	-5.9	76.6	2.86	9.15
6	5	-191.3	35.6	81.4	2.15	7.32
6	9	233.8	48.5	99.5	2.36	10.38
6	11	134.4	27.3	57.2	1.38	1.35
10	7	-173.5	-3.7	73.1	1.75	5.36
9	10	23.4	8.1	10.7	0.04	-2.45
10	11	-14.9	-6.2	6.7	0.05	-6.34
10	12	41.8	0.6	17.5	0.14	-3.93
11	12	88.6	9.1	37.1	0.36	-1.49

Table 4.0 Active Power Flow on Network Elements

Bus	1	2	3	4	5	6	7	8	9	10	11	12
Pi	418.2	75.5	351	302.7	250	-30	-352	-300	-207	-170	-210	-130

In the following are the parameters of the network elements and the nodal susceptance matrix is found as below:

$$
\begin{pmatrix}
122.736 & -73.1613 & 0 & 0 & 0 & -31.3562 & -18.2183 & 0 & 0 & 0 & 0 & 0 \\
-73.1613 & 142.647 & 0 & 0 & 0 & 0 & 0 & -69.4853 & 0 & 0 & 0 & 0 \\
0 & 0 & 101.067 & 0 & 0 & 0 & -54.8165 & -46.25 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 143.882 & -34.8701 & 0 & -74.5259 & 0 & 0 & 0 & -34.486 & 0 \\
0 & 0 & 0 & -34.8701 & 87.2435 & -52.3733 & 0 & 0 & 0 & 0 & 0 & 0 \\
-31.3562 & 0 & 0 & 0 & -52.3733 & 193.891 & 0 & 0 & -68.8554 & 0 & -41.3057 & 0 \\
-18.2183 & 0 & -54.8165 & -74.5259 & 0 & 0 & 198.968 & 0 & 0 & -51.4076 & 0 & 0 \\
0 & -69.4853 & -46.25 & 0 & 0 & 0 & 0 & 115.735 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -68.8554 & 0 & 0 & 171.355 & -102.5 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -51.4076 & 0 & -102.5 & 253.434 & -40.5263 & -59. \\
0 & 0 & 0 & -34.486 & 0 & -41.3057 & 0 & 0 & 0 & -40.5263 & 198.448 & -82.1296 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -59. & -82.1296 & 141.13
\end{pmatrix}
$$

From the nodal susceptance matrix the line 1 and column 1, corresponding to the slack bus, are removed (δe =0). The inverse matrix is computed resulting B^{-1}. The values of voltage angles are determined by using the relation (4.0).Then finally the power flow through the network element is calculated by using relation (5.0).

TABLULAR COLUMN 5.0

Active Power Flow on Network Elements

Line Number	Bus j	Bus k	P_{ljk} (MW)	$P_{lkj}(MW)$
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
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

By using the longitudinal susceptance matrix of network elements Bl applying relation (9.0) the **A** distribution factors are computed and tabulated as follows.

A distribution factors

-0.855434	-0.474534	-0.246909	-0.202962	-0.173702	-0.281587	-0.281587	-0.703219	-0.204932	-0.225911	-0.216403	-0.220378
-0.0744469	-0.270597	-0.44755	-0.54588	-0.611349	-0.369958	-0.369958	-0.152832	-0.541472	-0.494531	-0.515806	-0.506912
-0.0701196	-0.254869	-0.305541	-0.251158	-0.21495	-0.348454	-0.348454	-0.143949	-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	-0.216403	-0.220378
-0.0259832	-0.0944428	0.413567	0.246727	0.135646	-0.129121	-0.129121	-0.0533409	0.0950113	0.0677147	0.165509	0.124626
-0.288463	-0.0484975	0.804168	0.582375	0.434706	0.410227	0.410227	-0.592187	0.458001	0.473651	0.538632	0.511466
0.020946	0.076134	0.21022	-0.381309	-0.109349	0.10409	0.10409	0.0430002	-0.0338127	0.0169297	0.026553	0.0225299
-0.0353255	-0.1284	0.562265	0.335438	0.184417	-0.175547	-0.175547	-0.0725197	0.129173	0.0920617	0.225018	0.169435
0.0143794	0.0522658	0.227515	0.0458705	-0.075068	0.0714574	0.0714574	0.0295195	-0.09536	-0.108991	-0.251571	-0.191965
0.020946	0.076134	0.21022	0.618691	-0.109349	0.10409	0.10409	0.0430002	-0.0338127	0.0169297	0.026553	0.0225299
-0.0293923	-0.106834	-0.0950216	0.0541348	0.153443	-0.146063	-0.146063	-0.0603395	-0.527787	-0.31365	-0.135537	-0.209998
-0.0241085	-0.087629	-0.142308	0.0186759	0.125859	-0.119806	-0.119806	-0.0494925	-0.0474973	-0.163951	-0.353716	-0.274384
0.0391214	0.142197	0.00981545	-0.118681	-0.204234	0.194411	0.194411	0.0803125	-0.329355	-0.413407	-0.259176	-0.323653
-0.0293923	-0.106834	-0.0950216	0.0541348	0.153443	-0.146063	-0.146063	-0.0603395	0.472213	-0.31365	-0.135537	-0.209998
0.0052669	0.019144	-0.0461267	-0.0349424	-0.027496	0.0261735	0.0261735	0.0108124	0.0773364	0.147759	-0.21368	-0.0625784
0.00446223	0.0162192	-0.0390795	-0.029604	-0.0232952	0.0221747	0.0221747	0.00916052	0.065521	0.125184	-0.181034	-0.471073
-0.00446223	-0.0162192	0.0390795	0.029604	0.0232952	-0.0221747	-0.0221747	-0.00916052	-0.065521	-0.125184	0.181034	-0.528927

The **D DISTRIBUTION FACTORS** matrix is obtained represented below.

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

By applying the relation (13.0) **C FACTORS** are determined and tabulated in the following **Tabular column 6.0**

TABLE 6.0

C Distribution Factors

Line j-k	Cjk,7	Cjk,8	Cjk,9	Cjk,10	Cjk,11	Cjk,12
1-2	-0.140961	0.28674	-0.217666	-0.196637	-0.206154	-0.202170
1-6	-0.169625	-0.386754	0.001889	-0.045051	-0.023777	-0.032671
1-7	0.004445	-0.200156	-0.090413	-0.064452	-0.076225	-0.071299
2-8	-0.196225	0.225588	-0.272879	-0.251990	-0.261442	-0.257433
3-7	-0.030208	-0.106589	-0.254143	-0.227044	-0.323848	-0.283955
Line j-k	Cjk,7	Cjk,8	Cjk,9	Cjk,10	Cjk,11	Cjk,12
3-8	-0.2564791	0.745454	-0.306542	-0.319914	-0.387455	-0.357730
4-5	0.025595	0.032586	0.112308	0.112308	0.051955	0.055625
4-7	0.070066	-0.032625	-0.234654	-0.234654	-0.330580	-0.274916
4-11	-0.266474	-0.223654	-0.066561	-0.099564	0.056555	-0.003252
5-6	-0.208416	-0.147737	-0.070524	-0.070524	-0.130897	-0.126856
6-9	-0.231633	-0.324533	0.150009	0.150025	-0.242158	-0.167697
6-11	-0.124479	-0.194258	-0.196787	-0.196784	0.109231	0.030099
7-10	-0.427196	-0.313096	0.096571	0.096514	0.026396	0.090865
9-10	0.072534	-0.012398	-0.545471	-0.545214	0.062006	0.136740
10-11	-0.014476	0.000858	-0.065693	-0.0656936	0.227753	0.074525
10-12	-0.091720	-0.078706	-0.135062	-0.135662	0.111984	0.401528
11-12	-0.098400	-0.111535	-0.054999	-0.054996	-0.301547	0.408412

The transmission cost allocation process to the market participants is performed below. A unit cost of 2$/MW km is considered for the transmission lines.

The **Total Transmission cost** has been calculated and shows in the Tabular column 7.0

TABLE 7.0
Total Energy Transmission Cost

Bus i	Bus j	Unit Transmission cost ($/MW)	Pij (MW)	Total transmission cost($)
1	2	60	113.4	6804
1	6	140	191.9	26866
1	7	240	113.5	27240
2	8	60	189	11340
3	7	76	239	18164
3	8	90	111	9990
5	4	120	53.7	6444
4	7	56	172.9	9682.4
4	11	120	184.6	22140
5	6	80	196.3	15712

6	9	60	228.9	13716
6	11	100	129.9	12970
7	10	80	175.4	14024
9	10	40	20.6	820
11	10	100	15.1	1540
10	12	68	41.4	2808.4
11	12	50	88.9	4435
			TOTAL	204695.8

The **D distribution factors** are used to determine the transmission costs allocated to generators and shown in the following **Tabular column 8.0.**

TABLE 8.0

Transmission Costs Allocated To Generators

Cost allocated to generator 1($)	Cost allocated to generator 2($)	Cost allocated to generator 3($)	Cost allocated to generator 4($)	Cost allocated to generator 5($)	Cost allocated to generator 6($)	Total cost ($)
82945.7	9367.1	44195.8	28765.4	39421.8	1832.5	204695.8

TABLE 9.0

Transmission Cost 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

In case operating condition including the losses the results are shown in the following Tabular column **(10.0)** and **(11.0)** respectively, referring to generating units allocated costs.

TABLE 10.0

Transmission Cost Allocated To Generators (Including Losses)

Cost allocated to generator 1($)	Cost allocated to generator 2($)	Cost allocated to generator 3($)	Cost allocated to generator 4($)	Cost allocated to generator 5($)	Cost allocated to generator 6($)	Total cost ($)
85001.3	9367.1	44195.8	28765.4	39421.8	1832.5	208583.9

TABLE 11.0

Transmission Cost Allocated To Consumers (Including Losses)

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 ($)
52771.1	30446.4	36824.1	23541.9	38828.8	26171.5	208583.8

4.0 CONCLUSION

In case of deregulated power systems the transmission cost allocation method is presented.

There are several approaches, but the majority of them are dealing with simplified power flow computing techniques and for small scale power systems.

In this paper the AC power flow is used, the algorithm developed is also used for large scale power systems.

The results obtained by using the test system described are also proving the fact that the AC computing technology is leading to better results, than the ones obtained by using the DC approach.

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