THE ALLOCATION OF TRANSMISSION AND DISTRIBUTION LOSSES USING COOPERATIVE GAME THEORY

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Abstract: *This paper suggest a new analytical model relies on a fair schemes for the allocation of transmission and distribution losses to remove the restrictions to all electrical systems using cooperative game theory based on Nucleolus. Nucleolus depending on the cooperative game theory treat each electric current injection as an individual player for a fair allocation of transmission losses and provide an alternative and fast approach in the computational process without using of a series of linear programs and the create an effective economic signals, Nucleolus have been applied to the western Algerian network for 13 bus.*

Key words: *Restructured Power system, Methodology Mathematical, Cooperative game theory, Nucleolus, coalition, Transmission loss allocation.*

1. Introduction

Reformation of Electricity has taken several changes in many aspects of the electricity business. The motive behind this restructure is to compete in the electricity supply industry, specially the price of electricity by introducing a new concept of deregulation in the electricity market which is reflected dramatically in the development and growth of energy sector. Due to this change of electric system structure, several problems and challenges have arisen. One of the most important issues is the allocation of transmission losses among market participants, the participants must require a fair and equitable pricing structure that reflects both the share of power Generated/Consumed in the network and the cost of power losses caused by users [1, 2, 3]. The problem is how to apportion these amounts between workers (players) who pay the amount of the whole quota, in a simple and transparent way to have a reliable transfer of the project evaluation, which should be appropriate for each combination of market in all countries and the purpose behind this massage is to increase the efficiency and quality of services in the electricity supply and to increase more and to enhance the investment in the field of electric power [4, 5].
The transmission losses in a power network is influenced by a number of factors, including location of generating plants, load points, the types of connected loads, the network configuration, and the design of lines and transformers.
This paper dealt with several ways of pricing and methodologies, the costs of transport networks and losses due to this latter [6]. Such solutions insure an appropriate investment motivations to control power prices all over the world and to allow a skilful long-term use of power production capacity; the cooperative game theory is the simplest and most reliable way to deal with such issues [7]. This game theory is a set of analytical and mathematical tools to analyze cases of conflicts and/or cooperation in interests, it includes two theories: the cooperative game theory and non cooperative game theory [7, 8]. In particular, cooperative game theory (CGT) is the most convenient tool to solve transmission loss problem [9, 10]. The cooperative game theory (CGT) provides ways to assess economic budgets between the parties dealing in competitive markets and to end conflicts between these latter's using Nucleolus or Shapley value, those two methods are the most reliable as a tool of optimization in power systems [11, 12].
This paper proved the solutions to the engineering issues based on the cooperative game theory, such as allocation of the costs and the transport losses according to Nucleolus method [6, 12], which one of the most equitable methods to share the losses is comparing to other traditional ways [12,13]. The transmission loss is derived in the proposed approaches, the power generations and/or loads associated to the market transactions are modeled as individual current injections.

Three basic Performers are presented to determine individual current injections in the paper: the power losses, the real and imaginary tension are modeled first, to the generators (each generation), second to loads (each loads) and third generators and loads (each generation and load), a comparison was made between each model. The main difference is that the former treats the load demands as equivalent constant impedances based on a real-time solved AC power flow solution and accordingly to the bus impedance matrix (Zbus) is then modified, while the later formulates the load demands as equivalent current injections directly form a bus impedance matrix [9, 14-15]. Each current injection is then treated as an individual player of the transmission loss allocation game [4, 16-17]. The approaches are branch-current based, not branch-power-flow based. Without any approximations or assumptions like those made for a DC power flow or proportional sharing, the proposed approaches utilize the method of Nucleolus adopted from cooperative game theory to deal with the fairness issue of loss allocation [6, 7]. Some modified or alternative allocation approaches with or without a normalization procedure are also proposed to deal with the aggregated player of ancillary services and to speed up the computation when the number of players is large. The proposed approaches are consistent with the real-time AC power flow solution and recover the total system loss [18]. The Kirchhoff's laws and superposition principle are satisfied, both of the network configuration and the voltage-current relationships are reflected [19, 20].

The interactions of players are naturally and fully considered. Moreover, the effect of reducing transmission loss can be identified from the negative loss allocation and the negative allocation can provide economic signals for the players.

2. Allocation of transmission losses

2.1. Generation and Load Models

Based on a solved AC power flow solution for a pool based electric power market, let the complex power injection in to a generator bus i be $S_i^G = P_i^G + jQ_i^G$

Then the generation current injection is written as

$$I_i^G = \left[\frac{S_i^G}{V_i}\right] = -\left[\frac{P_i^G + Q_i^G}{V_i}\right] \qquad (1)$$

Where V_i is the bus voltage. Similarly let the complex power injection in to a load bus j be $S_i^G = P_i^G + jQ_i^G$ we can then have load current injection

$$I_i^D = \left[\frac{S_i^D}{V_i}\right]^* = -\left[\frac{P_i^D + Q_i^D}{V_i}\right]^* \qquad (2)$$

Or the equivalent load impedance:

$$Z_i^G = \left[\frac{V_i}{-I_i^D}\right]^* = -\left[\frac{|V_i|^2}{P_i^D - jQ_i^D}\right] \qquad (3)$$

The relationship between the voltage vector V_{Bus} the current vector may I_G be expressed as:

$$[V_{Bus}] = [Z_{Bus}][I_{Bus}] \qquad (4)$$

When Z_{Bus} is the impedance matrix.

$$\begin{bmatrix} V_1^n \\ . \\ . \\ V_i^n \\ . \\ . \\ V_N^n \end{bmatrix} = \begin{bmatrix} Z_{11} & . & . & Z_{1n} & . & . & Z_{1N} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ Z_{i1} & . & . & Z_{in} & . & . & Z_{iN} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ Z_{N1} & . & . & . & . & . & Z_{NN} \end{bmatrix} \qquad (5)$$

2.2. Transmission branch losses model

The lumped transmission line π-model between buses m and n as shown in fig1, where $Z_{mn} = r_{mn} + jx_{mn}$ the serial impedance and jb_c is the shunt susceptance. After calculating the individual voltage contribution to each bus from every current injection, we can then calculate the individual current contribution to each line from every current injection [16, 17].

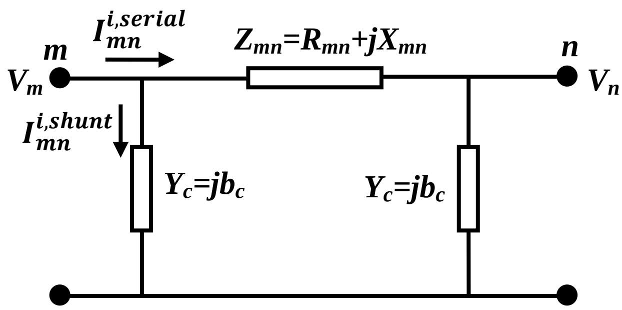

Fig.1. Schematic of a transmission line π-model between the bus m and n

The current contribution to the transmission line m-n, measured at bus m, by current injection I_i as

$$I_{mn}^i = I_{mn}^{i,serial} + I_{mn}^{i,shunt} = \frac{V_m^i - V_n^i}{r_{mn} + jx_{mn}} + V_m^i . jb_c \qquad (6)$$

The active power loss of line m-n can be calculated as

$$_{loss}P = \left|I_{mn}^{i,serial}\right|^2 r_{mn} = \left|\frac{V_m^i - V_n^i}{r_{mn} + jx_{mn}}\right|^2 r_{mn} \qquad (7)$$

In addition, the reactive power loss of the line can also be calculated by the $\left|I_{mn}^{i,serial}\right|^2 r_{mn} - \left(\left|V_m\right|^2 + \left|V_n\right|^2\right)\ b_c$, if needed and the individual reactive loss contribution by a current injection I_i is equal to

$$\left|I_{mn}^{i,serial}\right|^2 r_{mn} - \left(\left|V_m^i\right|^2 + \left|V_n^i\right|^2\right)\ b_c \quad (8)$$

3. Cooperative game

Cooperative games have the following ingredients

1) A set of players

Let $N = \{1,2,3....n\}$ be the finite set of players and Let i, where i, runs from 1 through n, index the different numbers of N.

2) A characteristic function, specifying the value created by different subsets of the players in the game, is denoted by v. The Characteristic function is a function expressed as a number and is associated with every subset S of N $(S \subset N)$, denoted by $v(S)$.

The number $v(S)$ is interpreted as the value created when the members of S come together and interact. Into to, a cooperative game is a pair (N,v), where N is a finite set and v is a function mapping subsets of N to members of the game.

3) Imputation:

For a Given Cooperative Game (N,v), an allocation $X = (x_1, x_2, x_3.........x_n)$ is called as an imputation.

iv) A key concept in cooperative game theory is the *core* of the game. The Core is defined as a set of imputations satisfying the following conditions.

$$x(i) \geq v(i) \qquad i \in N \quad (9)$$

$$x(S) \geq v(S) \qquad S \subset N \quad (10)$$

$$x(N) = v(N) \quad (11)$$

Any pay-off vector satisfying the above conditions is called an imputation. Core is a solution concept in Game Theory that gives a set of imputations satisfying the above three rationalities. There are numerous methods for allocation of costs amongst the players of a cooperative game. Here, Nucleolus and Shapley Value for obtaining a particular solution are discussed [7, 8-12].

3.1. Transmission loss allocation game

In the concept of Nucleolus solution, the dissatisfaction for every coalition is minimized till the solution becomes fair and acceptable for all the coalitions and the players as well [7, 12]. A measure of inequality of an imputation ‘ X ’ for a coalition S is defined as the excess, $e(X:S) = v(S) - \sum_{i \in S} x_i$ (12)

The Nucleolus can be calculated by using linear programming, the objective is to minimize function of the maximum excesses (dissatisfaction) vector over the non-empty set of imputations, represented as

$$\min \varepsilon \in (S)$$

$$\sum_{i \in S} X_i - v(S) \leq \min \varepsilon \qquad (\forall S \subset N) \quad (13)$$

$$\sum_{i \in N} x_i = v(N) \quad (14)$$

Subject to

$$y(S) \geq (v(S))^2 + \in (S) \quad (15)$$

$$y(N) = (v(N))^2 \quad (16)$$

If the solution to the game is

$$y = \begin{bmatrix} y_1^\bullet & y_2^\bullet & \dots & y_{n-1}^\bullet & y_n^\bullet \end{bmatrix}^T \quad (17)$$

Then the relationship between the solution vectors is

$$y = v(N)x \quad (18)$$

Multiply equations (10) by $v(N)$

$$x(S).v(N) = v(S).v(N) \quad (19)$$

In a balanced cooperative game it is understood that

$$x(S) \cup x(S') = x(N) \quad (20)$$

$$v(S) + v(S') = v(N) \quad (21)$$

Where S' is the conjugate of coalition S

$$y(S) = (v(S))^2 + v(S).v(S') \quad (22)$$

$$y(N) = (v(N))^2 \quad (23)$$

By comparing equations (15&22) the minimum value of the lexicographical excess vector is determined.

$$e(S) = v(S).v(S') = e(S') \quad (24)$$

Hence, it is proved and the proof can be extended to all coalition values which are real as well as complex numbers, which exhibits balancing condition. The equations 15&16 are modified for complex numbers

$$y(S) \geq \left|v(S)\right|^2 + \in (S) \quad (25)$$

$$y(N) = \left|v(N)\right|^2 \quad (26)$$

For a 'm' node power network having 'n' generator buses the transmission loss of element 'ij' connected between nodes 'i' and 'j' is derived in terms individual current contribution of each generator as

$$ {}_{loss}P_{ij} = \left(\sum_{k=1}^{m} {}_{ij}I_k \right)^* \cdot \left(\sum_{k=1}^{m} {}_{ij}I_k \right) . R_{ij} \quad (27) $$

Where ${}_{ij}I_k$ is the current contribution of $'k'$ generator to the element $'ij'$ and it can be determined from modified Y bus method using converged load flow solution.

R_{ij} is the resistance of line element $'ij'$ connected between nodes $'i'$ and $'j'$.

The individual voltage contribution of each generator is derived in terms of current injections.

$$ v_{nn} = \begin{vmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{vmatrix}^{-1} .diag \begin{vmatrix} I_G \\ 0 \end{vmatrix} \quad (28) $$

v_{nn} is a square matrix of size 'm' and the columns n+1 to n will be zero since they are load buses.

$$ {}_{ij}I_k = (v_{ik} - v_{jk}) / Z_{ij} \quad (29) $$

Where Z_{ij} is the transmission line impedance of element $'ij'$ (pi model for transmission line is considered).

It can be observed that the branch current flowing through is the algebraic sum of individual current contributions of each generator

$$ \sum_{k=1}^{n} {}_{ij}I_k = I_{ij} \quad (30) $$

For each element $'ij'$ the coalitions present a balancing condition because of Kirchhoff's current law. Let $'S'$ be set of possible coalitions

$$ x(S) = I(S) \quad (31) $$

$$ x(N) = I_{ij} \quad (32) $$

Let the solution vector for this balanced cooperative game is

$$ {}_{ij}x = \lfloor {}_{ij}I_1 \quad {}_{ij}I_2 \quad \dots \quad {}_{ij}I_n \rfloor \quad (33) $$

Now the coalition values for the transmission loss allocation problem is derived as

$$ \min \varepsilon(S) $$

$$ y(S) \geq (I(S).I^*(S)) + \in(S) \quad (34) $$

$$ y(N) = |I_{ij}|^2 \quad (35) $$

$$ {}_{ij}y = real\left(I_{ij}^* \cdot {}_{ij}x\right) \quad (36) $$

The transmission loss contribution of $'k'$ generator to $'ij'$ th element is determined as

$$ {}_{ij}P_k = {}_{ij}y_k . R_{ij} \quad (37) $$

Now the transmission loss contribution of $'k'$th generator is the summation of losses to every line element of that generator.

$$ {}_{loss}P_k = \sum_{ij} {}_{ij}P_k \quad (38) $$

4. Results and Discussion

To analyze the effect of applying the proposed methodology, in this paper, simulations have been performed on Western Algeria Network a13 bus systems are presented and discussed. The one-line diagram of a 13 bus system with 4 generation buses, 9 load buses, and 15 transmission lines is shown in Fig. 2.

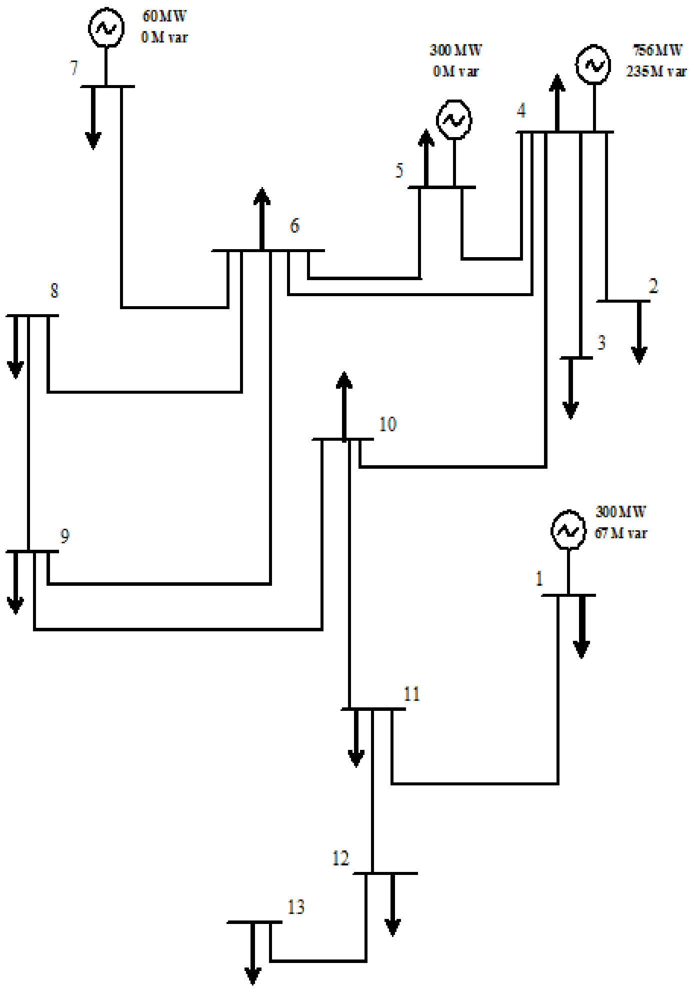

Fig.2. Western Algeria Network a 13 bus systems

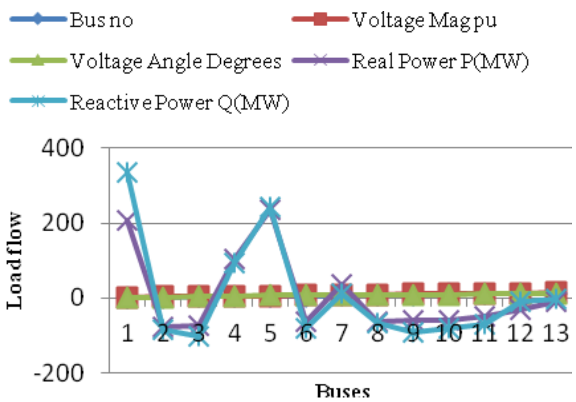

Fig.3. Converged load flow solution of Western Algeria Network a13 bus systems

Fig.3 shows the detailed analysis result when applying the cooperative game theory based on Nucleolus on the western Algerian Electrical network, and the calculation of changed values of the angle, tension and power active and reactive in each bus, depending on each bus type, if it is a generator or a load, then it is the solution of power flow for Electrical network.

Table 1 Transmission loss allocation (only generator buses)

Line N°	G1 (MW)	G4 (MW)	G5 (MW)	G7 (MW)	Loss
1	0.1132	0.0495	0.1130	0.0132	0.2889
2	0.1134	0.0496	0.1132	0.0132	0.2894
3	-0.0863	-0.0208	0.5796	0.0052	0.4777
4	0.2768	0.0299	0.0965	0.0123	0.4155
5	0.2894	-0.1753	0.2708	0.0200	0.4049
6	0	0.4007	0	0	0.4007
7	0.0676	-0.0031	0.5240	-0.0093	0.5792
8	0.1245	0.0673	0.1536	-0.0056	0.3398
9	0.4850	0.1970	0.5114	0.0685	1.2619
10	0.4119	0.1533	0.4479	0.0667	1.0798
11	0.0131	0.0014	0.0170	0.0038	0.0353
12	0.0687	-0.0256	0.0671	0.0020	0.1122
13	0.0522	-0.0818	0.0494	0.0051	0.0249
14	0.0439	0.0205	0.0455	0.0055	0.1154
15	0.1322	0.0619	0.1371	0.0166	0.3478
Total	2.1056	0.7245	3.1261	0.2172	6.1734

Table 1 shows that the losses allocated to generators are 2.1056, 0.7245, 3.1261 and 0.2172 pu, respectively.

The total allocated loss is consistent with the power flow solution and can reasonably reflect the amounts of transaction

Table 2 Transmission loss allocation (only load buses)

Line N°	L2 (MW)	L3 (MW)	L6 (MW)	L8 (MW)	L9 (MW)	L10 (MW)	L11 (MW)	L12 (MW)	L13 (MW)
1	0.2889	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.2895	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0924	0.0915	0.0378	0.0388	0.0467	0.0639	0.0538	0.0338	0.0190
4	-0.0042	-0.0226	0.1183	0.0966	0.1090	0.0432	0.0360	0.0256	0.0137
5	-0.0555	-0.0423	-0.0070	0.0110	0.0362	0.1592	0.1304	0.1156	0.0572
6	0.0563	0.0590	0.0512	0.0492	0.0530	0.0496	0.0384	0.0289	0.0151
7	0.0420	0.0420	0.1086	0.1007	0.1025	0.0691	0.0583	0.0358	0.0202
8	0.0478	0.0490	0.0422	0.0415	0.0439	0.0435	0.0367	0.0225	0.0127
9	0.1586	0.1875	0.1578	0.1882	0.1496	0.1589	0.1341	0.0810	0.0462
10	0.1361	0.1635	0.1372	0.1374	0.1187	0.1383	0.1147	0.0882	0.0458
11	0.0044	0.0058	0.0046	-0.0021	0.0033	0.0055	0.0042	0.0067	0.0028
12	0.0123	0.0084	-0.0072	-0.0086	-0.0344	0.0631	0.0557	0.0111	0.0117
13	-0.0141	-0.0154	-0.0132	-0.0124	-0.0140	-0.0131	0.0512	0.0364	0.0194
14	0.0264	0.0298	0.0254	0.0232	0.0273	0.0254	0.0208	-0.0407	-0.0222
15	0.0553	0.0582	0.0505	0.0483	0.0524	0.0491	0.0381	0.0290	-0.0330
Total	0.8467	0.9039	0.7062	0.7118	0.6942	0.8557	0.7724	0.4739	0.2086

Table 2 shows that the losses allocated to loads are 0.8467, 0.9039, 0.7062, 0.7118, 0.6942, 0.8557, 0.7724, 0.4739 and 0.2086 pu, respectively.

The total allocated loss is consistent with the power flow solution and can reasonably reflect the amounts of transactions.

Table 3 Transmission loss allocation (generator and load buses)

Line N°	G1 (MW)	L2 (MW)	L3 (MW)	G4 (MW)	G5 (MW)	L6 (MW)	G7 (MW)	L8 (MW)	L9 (MW)	L10 (MW)	L11 (MW)	L12 (MW)	L13 (MW)
1	0.0000	0.2889	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.2895	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.6780	-0.1133	-0.1947	0.1089	0.9385	-0.1929	-0.0324	-0.1415	-0.2264	-0.1747	-0.1648	0.0124	-0.0193
4	-1.1349	0.3178	0.3776	-0.4028	-0.9491	0.4524	-0.0355	0.3809	0.4870	0.3854	0.3394	0.1118	0.0856
5	2.2055	-0.9175	-0.8551	0.8580	2.5932	-0.7447	0.3628	-0.7518	-0.7012	-0.5882	-0.4819	-0.3789	-0.1952
6	0.0000	0.0000	0.0000	0.4007	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7	-0.3528	0.2665	0.1852	-0.4312	-0.3830	0.2597	-0.2063	0.3003	0.2217	0.2178	0.1615	0.2375	0.1024
8	-2.6917	0.4186	0.7602	-0.2650	-0.8781	0.5767	0.2218	0.3651	0.7444	0.6031	0.5854	-0.1379	0.0372
9	-1.4695	-1.4855	-0.2778	2.7031	5.2418	-0.5935	1.8983	-1.2764	-0.1009	-0.5436	-0.1616	-1.9858	-0.6867
10	-1.2251	-1.3312	-0.2691	2.3856	4.6837	-0.5439	1.6833	-1.1698	-0.1235	-0.5011	-0.1647	-1.7396	-0.6049
11	-0.0292	-0.0562	-0.0163	0.0923	0.1943	-0.0261	0.0664	-0.0561	-0.0112	-0.0239	-0.0110	-0.0646	-0.0232
12	-0.7225	0.1062	0.2016	-0.1043	-0.2041	0.1362	0.0714	0.0735	0.1572	0.2146	0.2068	-0.0405	0.0159
13	0.0550	-0.0202	-0.0202	-0.0784	0.0567	-0.0180	0.0068	-0.0178	-0.0185	-0.0181	0.0467	0.0331	0.0177
14	-0.4799	-0.1472	0.0459	0.3235	0.5832	-0.0147	0.2718	-0.1321	0.0702	-0.0056	0.0414	-0.3264	-0.1147
15	-1.7174	-0.0064	0.3745	0.2909	0.3514	0.2236	0.4398	-0.0100	0.3978	0.2434	0.2921	-0.3937	-0.1382
Total	-6.8845	-2.6795	0.6013	5.8813	12.2285	-0.4852	4.7482	-2.4357	0.8966	-0.1909	0.6893	-4.6726	-1.5234

According to the results high loss shares indicate that the associated shared transmission branches are heavily loaded. It can also be seen that the loss allocated to a generator or load bus is mainly contributed by those lines which are directly connected with that bus and are heavily loaded.

Table 4 the total losses when the system applied this method only on generators, loads and both.

	Generator	Load buses	Generator and Load buses
G1 (MW)	2.1056	-	-6.8845
L2 (MW)	-	0.8467	-2.6795
L3 (MW)	-	0.9039	0.6013
G4 (MW)	0.7245	-	5.8813
G5 (MW)	3.1261	-	12.2285
L6 (MW)	-	0.7062	-0.4852
G7 (MW)	0.2172	-	4.7482
L8 (MW)	-	0.7118	-2.4357
L9 (MW)	-	0.6942	0.8966
L10 (MW)	-	0.8557	-0.1909
L11 (MW)	-	0.7724	0.6893
L12 (MW)	-	0.4739	-4.6726
L13 (MW)	-	0.2086	-1.5234
Total	6.1734	6.1734	6.1734

Table 4 the comparison of the obtained results when applying the cooperative game theory using Nucleolus. We note that the values of calculated losses are equal and this distinguish this method from the traditional ones it can be used on generator loads or both of them, and it gives desired results in a small period of time and with less transport losses, the objective behind that is to enhance the organization of the network.

The objective behind this method is also to maintain the stability of imaginative and real value of tension in the electrical grid, as shown in Fig.4.

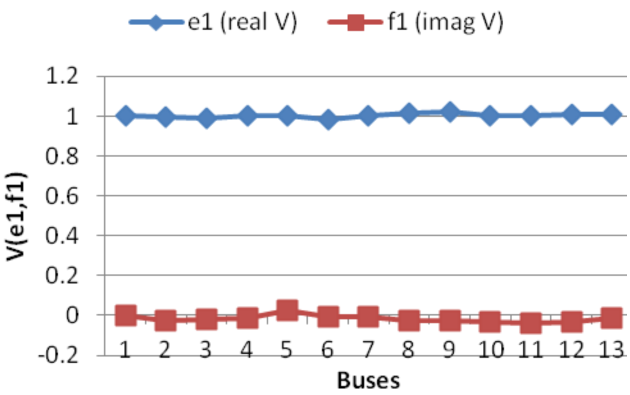

Fig.4. The value of the Real and fictitious voltage of Western Algeria Network a13 bus systems

5. Conclusion

The objective of this study is to give an efficient analytic method to solve the problem of power transmission losses allocation in a fair and acceptable way using the cooperative game theory and based on Nucleolus, this method is based on matrixes methodology which makes it an easy method to be applied on a large power network. According to the obtained result, Nucleolus offers a direct and stable solution and does not get affected by the problem dimensionality's, There is no need to determine the losses division factors which will be allocated to the supply-side and demand-side, Also we can note that Nucleolus method offer the exact motivation for players to join the coalition in the appropriate location to achieve good distribution of power with lower transmission losses and thus reduce the costs.

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