CONTINGENCY-CONSTRAINED CONGESTION MANAGEMENT TRANSMISSION COST ALLOCATION

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Abstract - Although there is a growing concern in this field, designing power markets and determining the transmission price are becoming more and more difficult due to the rapid deregulation advancement. Moreover, the operation of the transmission grid is restricted by the equipment limits used for power generation and transmission. The case study is carried out on a real large scale system, representing the system based on the South-Western side of the Romanian Power System.

Keywords: congestions; transmission system; territorial operator; real power allocation; transmission costs.

1. INTRODUCTION

Shortly after becoming obvious that the power industry will be reorganized, it was admitted that for stimulating competition on the power market and for offering open access to the transmission grid, operating conditions close to the limit and several over the limit (congestions) may occur. An important number of power transactions have been anticipated in the context of raising competition [1], [2]. This leads to overloads of the transmission lines. The overloads will cause the system to operate over the allowable values for contingency limits, thermal limits, stability limits and voltage limits, which can affect the power transmission equipment.

These limits are just power flow limits and they depend on the operating condition of the power system at a given moment [11]. Contingency limits ensure that no other system element is overloaded when another one is disconnected. For this, *N-1* and *N-2* criteria must be satisfied. To ensure safety and power balance in the system, the transmission grid operator must respect these constraints. This means that some generators cannot operate, because the power they produce will overload the system.

The problem of congestions has an economical side also [3], [4]. If there are no overloads in the system, then marginal costs corresponding to buses have very close values, the differences occur because of the transmission losses. In this case, the generated power will be distributed depending on the offered price (classic power flow optimization). The occurrence of congestion will lead to an important growth of the marginal cost and the generated power distribution will depend not only on the offered price but also on the "cost" of the congestion. The system operator will act to eliminate the congestion.

Power transactions are completed under the supervision of the transmission and system operators or the dispatchers [5], [6]. Each supplier must produce enough energy to cover the demand and the system losses. Basic information concerning the following aspects is needed: knowing the path of real power from a generator to a consumer, the quantitative distribution of the generated power for each user and the electricity transmission costs allocation. No one must be surprised that there are at least five methods for determining allocation [5]-[11], because every method has its own advantages and disadvantages, accepts simplifications or refers partially to domains.

The Bialek tracing method allows assessment of how much of active and reactive power output from a particular generator goes to a particular consumer. The method has two algorithms: upstream-looking algorithm (generation-load) or downstream-looking algorithm (load-generation) [10], [11]. In case of the first algorithm the costs for the use of transmission network are allocated to individual generators and real power losses are allocated to consumers. The downstream-looking algorithm allocates the costs for using the transmission network to individual consumers and real power losses are allocated to generators. The transmission costs for Bialek method can be calculated using traditional MW-km approach. This approach is based on the active power flows and transmission line lengths in km.

This paper proposes to the occurrence of congestions in case of *N-2* contingencies. The case study is carried out on a large scale power system, which includes the Western, Southwestern and Northwestern parts of the Romanian Power System. The measures to be taken to eliminate the congestions are indicated. The authors analyze the Bialek method to determine the contribution of generators active power flow, considering the real system regime with power losses and use the MW-km method to computing the transmission costs allocated to generators.

2. BIALEK METHOD

Consider line *i-j* connecting a sending bus *i* with receiving bus *j*. Both buses are connected to the rest of system. Active power flow from from bus *i* to bus *j* is P_{ij} and active power flow from from bus *j* to bus *i* is P_{ji}. The transmission loss in line *i-j* is $\Delta P_{ij} = |P_{ji}| - |P_{ij}|$. The gross power is defined as the sum between consumed power and the part allocated from total transmission losses. The gross real power flow through bus *i*, P_i^b , can be expressed as:

$$P_i^b = \sum_{j\in N_i} \left|P_{ij}^b\right| + P_{gi}\ ; \quad i \in N \tag{1}$$

where:

N_i - subset of buses supplying directly bus *i*;

P_{ij}^b - gross real line flow through the network elements *i-j*;

P_{gi} - real generated power in bus *i*.

The term $\left|P_{ij}^b\right|$ can be replace by $(P_{ij}^b / P_j^b)P_j^b$. Considering the real power loss, the relation (1) becomes:

$$P_i^b - \sum_{i\in N_i}\left(\frac{\left|P_{ji}\right| - \Delta P_{ij}}{P_j}\cdot P_j^b\right) = P_{gi} \tag{2}$$

where:

P_{ji} - real power flow through the network elements *i-j*;

P_j - real power injected in bus *j*.

The matrix form of relation (2) is:

$$P_g = A^{g\text{-}c}\cdot P^b \tag{3}$$

where:

P^b - array of gross bus flows;

P_g - bus generation array;

$A^{g\text{-}c}$ - the upstream distribution matrix having its elements defined by relation:

$$a_{ij}^{g\text{-}c} = \begin{cases} 1 & if \quad i = j \\ -\dfrac{\left|P_{ji}\right| - \Delta P_{ij}}{P_j} & if \quad i > j,\ j \in N_i \\ 0 & if \quad i > j,\ j \notin N_i \ \ or\ \ i < j \end{cases} \tag{4}$$

From relation (3) results P_i^b for each bus:

$$P_i^b = \sum_{k\in N}(ai_{ik}^{g\text{-}c}\cdot P_{gk})\ ; \quad i \in N \tag{5}$$

The net power is defined being the difference between the generated power and the part allocated from total transmission losses. The net real power flow through bus *i*, P_i^n, can be expressed as:

$$P_i^n = \sum_{j\in N_i} \left|P_{ij}^n\right| + P_{ci}\ ; \quad i \in N \tag{6}$$

where:

N_i - subset of buses supplying directly bus *i*;

P_{ij}^n - the net real line flow through the network elements *i-j*,

P_{ci} - real consumed power in bus *i*.

As an analogy with the previous algorithm, the relation (6) can be written as:

$$P_i^n - \sum_{i\in N_i}\left(\frac{\left|P_{ji}\right| - \Delta P_{ij}}{P_j}\cdot P_j^b\right) = P_{ci} \tag{7}$$

which in matrix form means:

$$\boldsymbol{P_c} = \boldsymbol{A}^{c\text{-}g}\cdot \boldsymbol{P}^n \tag{8}$$

where:

P^n - net bus flow array;

P_c - consumed power array;

$A^{c\text{-}g}$ - the downstream distribution matrix, its elements being defined as following:

$$a_{ij}^{c\text{-}g} = \begin{cases} 1 & if \quad i = j \\ -\dfrac{\left|P_{ji}\right| - \Delta P_{ij}}{P_j} & if \quad i < j,\ j \in N_i \\ 0 & if \quad i < j,\ j \notin N_i \ \ or\ \ i > j \end{cases} \tag{9}$$

From relation (8) results P_i^n for each bus:

$$P_i^n = \sum_{k\in N}(ai_{ik}^{c\text{-}g}\cdot P_{ck})\ ; \quad i \in N \tag{10}$$

The transmission cost can be calculated for both generators and consumers using MW-km method. The following formula will be used:

$$C_{tu} = C_T\cdot\frac{\sum_{ij\in L}(c_{ij}\cdot \ell_{ij}\cdot P_{ij\,u})}{\sum_{k\in U}\sum_{ij\in L}(c_{ij}\cdot \ell_{ij}\cdot P_{ij\,k})} \tag{13}$$

where:

C_{tu} – transmission hourly cost for transaction *u* [\$/h];

L_{ij} – length of line *ij* [km];

c_{ij} – unit transmission cost of line *ij* [\$/MW · km];

$P_{ij\,u}$ – real power flow on line *ij*, due to transaction *u* [MW];

U – set of transactions,

L – set of lines.

For upstream-looking algorithm the term P_{ji} is determined as:

$$P_{ij}^{generator} = \frac{P_{ij}^b}{P_i^b}\sum_{k\in N}(ai_{ik}^{g\text{-}c}\cdot P_{gk}) \tag{14}$$

and for downstream-looking algorithm

$$P_{ij}^{consumer} = \frac{P_{ij}^n}{P_i^n}\sum_{k\in N}(ai_{ik}^{c\text{-}g}\cdot P_{ck}) \tag{15}$$

3. CASE STUDY

The power system based on the South-Western side of the Romanian Power System is used as a case study. It has 88 buses, 35 sources and 42 consumers. The obtained operating condition in case of simultaneously disconnection of one circuit of the double circuit 220 kV OHL P.D.F.A-Resita, respectively Resita-Timisoara is presented in figure 1.

These simultaneous disconnections caused the overloading to 107% of the second line circuit of PDFA-Resita. Bus voltage levels are within the admissible domain. Hourly system operation cost is 126,667 \$/h and the penalty cost is low (15,254.5 \$/hr).

For local marginal prices, the maximum value is obviously localized in Resita and Iaz area and minimum values belong to P.D.F.A, Calafat and Turnu-Severin areas. To eliminate the congestion the power consumption in Resita A, Resita and Resita B buses has been reduced with 65 MW by the TSO. The hourly cost value is 122522.72 $/h. All local marginal prices are around 42 $/MWh value.

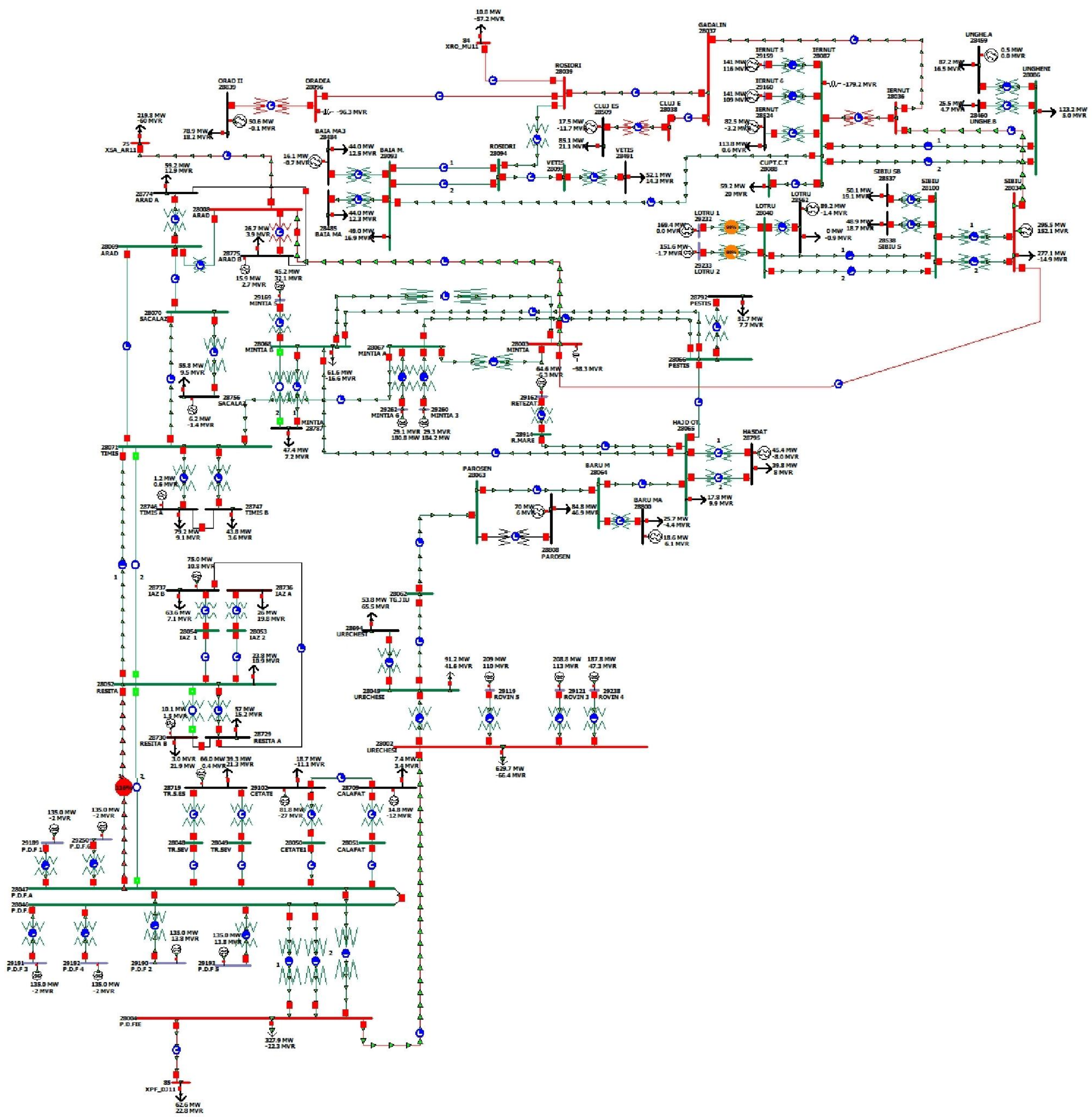

Fig. 1. Operating condition with congestion on Portile de Fier-Resita OHL

The obtained operating condition after solving the congestion is presented in fig.2. Also, the generated power at PDF groups, Iernut and Sibiu has been reduced. In case of the Rovinari 5, Paroseni, Mintia 3 and Mintia 6 generating units, the power has been increased. Another category of groups has the same value (Hasdat, Calafat, Tr.S.ES, Sacalaz, Lotru). The redispatching mechanism is presented in Table I.

Table 1. Redispatching the generating units

Generator Name	P.D.F.6	LOTRU 2	MINTIA 6	MINTIA 3	RETEZAT1	P.D.F 5	LOTRU 1	P.D.F 2	P.D.F 3
Congestion	135.0	151.6	180.8	184.2	64.6	135.0	169.4	135.0	135.0
Without congestion	125.6	152.1	140.0	140.0	100.0	125.6	170.0	125.6	125.6
Generator Name	**P.D.F 4**	**P.D.F 1**	**MINTIA 5**	**IERNUT 6**	**IERNUT 5**	**ROVIN 3**	**ROVIN 5**	**ROVIN 4**	**BARU MA**
Congestion	135.0	135.0	45.2	141.4	141.4	208.8	208.8	187.8	18.6
Without congestion	125.6	125.6	46.0	162.9	147.0	210.0	210.0	205.0	18.6

Generator Name	**HASDAT**	**CALAFAT**	**ARAD B**	**SACALAZ**	**LOTRU**	**BAIA MA3**	**TIMIS A**	**IAZ B**	**IERNUT**
Congestion	45.4	14.8	15.9	6.2	89.2	16.1	1.2	75.0	82.5
Without congestion	45.4	14.8	15.9	6.2	89.2	16.1	1.2	75.0	82.5
Generator Name	**CETATE**	**RESITA B**	**ORAD II**	**PAROSEN**	**TR.S.ES**	**CLUJ ES**	**UNGHE.A**	**SIBIU**	
Congestion	81.8	10.1	50.6	70.0	66.0	17.5	0.5	295.5	
Without congestion	81.8	10.1	50.6	70.0	66.0	17.5	0.5	300.0	

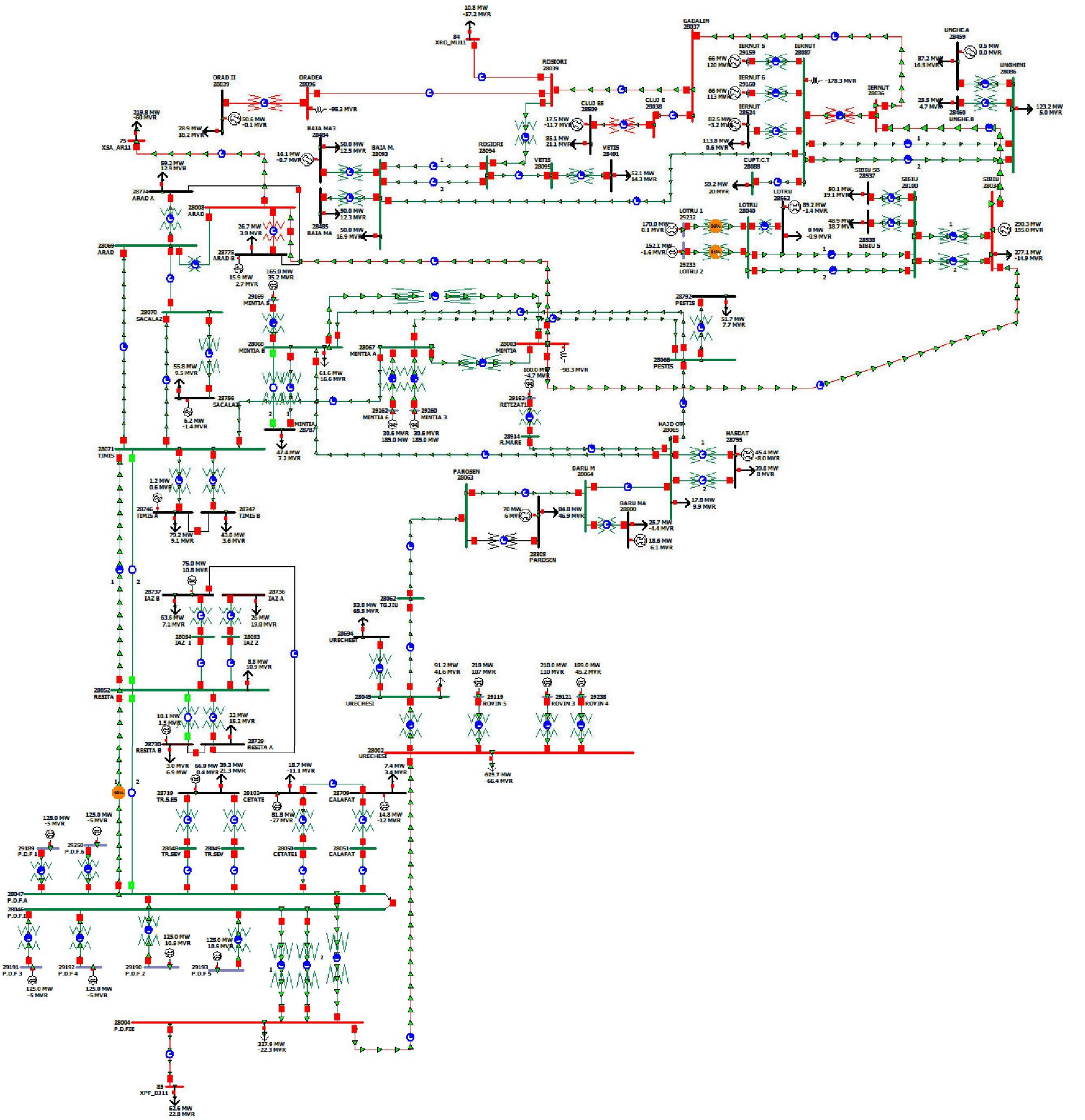

Fig.2. Operating condition with congestion solved on Portile de Fier-Resita OHL

For the computing of the transmission cost allocated to generators, Mathematica® environment has been used. The application software TAPQ (Tracing for Real and Reactive Power) has been developed by the author [11].

This application is applied for regime with congestion (Figure 1) and regime with congestion solved (Figure 2). In the following the results for generators contribution on line and transmission cost allocated to generators are analyzed.

The contribution of each generator to real power flow through the network elements is computed using the relation (14). Some of values obtained are presented in Table II, containing the contribution of generators to lines P.D.F.A – Resita, Resita-Timis, P.D.F.A – P.D.FIE and P.D.FIE – Urechesti before and after congestion is solved. It can be observed that in both cases groups of P.D.F has the significant contribution, followed by generator of bus Cetate.

For lines P.D.F.A – Resita and P.D.FIE – Urechesi the contribution of each P.D.F group is diminished from 68.7 MW to 57.58 MW and from 25.83 MW to 24.98 MW. These values belong to groups P.D.F 1, 2 and 6.

Also, it should be mentioned the same contribution of groups P.D.F 3, P.D.F 4 and P.D.F 5 on line P.D.FIE – Urechesi for 46.92 MW after resolving the congestion.

Table 2. The contribution of generators on lines

	Line Resita – Timis	
Generators	**Congestion**	**Without congestion**
P.D.F 1	36.62373	44.2407
P.D.F 6	36.62373	44.2407
P.D.F 2	36.62373	44.2407
CALAFAT	6.646528	8.770648
CETATE	12.09939	15.78012
TR.S.ES	7.161973	9.299001
IAZ B	1.020921	2.228129
P.D.F 3	0	0
P.D.F 4	0	0
P.D.F 5	0	0
Total [MW]	136.8	168.8

	Line PDFA - PDFIE	
Generators	**Congestion**	**Without congestion**
P.D.F 1	12.15389	15.45217
P.D.F 6	12.15389	15.45217
P.D.F 2	12.15389	15.45217
CALAFAT	1.004445	1.386479
CETATE	5.216549	7.188494
TR.S.ES	2.376762	3.247909
IAZ B	0	0
P.D.F 3	134.5802	125.3402
P.D.F 4	134.5802	125.3402
P.D.F 5	134.5802	125.3402
Total [MW]	448.8	434.2

	Line PDFIE – Urechesi	
Generators	**Congestion**	**Without congestion**
P.D.F 1	25.82796	24.98044
P.D.F 6	25.82796	24.98044
P.D.F 2	25.82796	24.98044
CALAFAT	2.134523	2.241422
CETATE	11.08557	11.62113
TR.S.ES	5.050802	5.250665
IAZ B	0	0
P.D.F 3	52.71507	46.91516
P.D.F 4	52.71507	46.91516
P.D.F 5	52.71507	46.91516
Total [MW]	253.9	234.8

For determining the transmission costs allocated to generators, the unit cost of transmission lines of 2 $/MW·km is considered. The results obtained are presented in Table III. For system analyzed, generators from buses Unghe.A, Timis A, Sacalaz, Baia Ma3, Cluj Es, Orad II, Parosen and Iernut supplies only the local consumers. For these generators the transmission cost is 0 $/h.

We should expect in both cases (with congestion and with congestion solved), that the cost allocation to generator Sibiu (2577.79 $/h and 2658.64 $/h) to be much higher in value that the cost allocation to generator Mintia 3 (1853.61 $/h and 1497.90 $/h), because generator Sibiu uses the transmission network much more. Active power generated for generator Sibiu is 295.5 MW (regime with congestion) and 300 MW (regime with congestion solved).

According to the results shown in Table I some generators produced the same value of active power in both cases. For these generators the transmission cost in case of regime with congestion solved is greater than in case of regime with congestion. Generators Calafat, Cetate and TR.S.ES are some of these examples. This is due to dispatching the generating group P.D.F 1, P.D.F 2 and P.D.F 6 and reducing the consumed power in Resita A, Resita and Resita B buses.

The smallest values of transmission cost are alocated to genetators Baru Ma (2.19 $/h, 2.24 $/h), Arad B (0.00001 $/h, 0.00004 $/h) and Resita B (0 $/h, 0.0002 $/h), because of the smallest uses of transmission network. The cost allocate to generator Resita B is zero in case of regime presented in Figure 1, because supply only to local consumer.

Table 3. Transmission cost allocated to generators

	Transmission cost allocated to generator [$/h]								
	P.D.F 1	**P.D.F 6**	**P.D.F 2**	**Calafat**	**Cetate**	**TR.SEV**	**P.D.F 3**	**P.D.F 4**	**P.D.F 5**
Congestion	995.03	995.03	995.03	140.87	559.44	201.32	1109.28	1109.28	1109.28
Congestion solved	997.02	997.02	997.02	152.47	596.23	216.41	1038.77	1038.77	1038.77
	Mintia 3	Mintia 6	Rovin 3	Rovin 5	Rovin 4	Hasdat	Retezat1	Mintia 5	Lotru
Congestion	1853.61	1819.26	1913.62	1913.56	1721.31	196.22	403.46	338.26	1221.86
Congestion solved	1497.90	1497.90	1960.36	1960.36	1914.45	203.29	642.89	344.50	1240.52
	Lotru 1	Lotru 2	Sibiu	Iernut 5	Iernut 6	Baru Ma	Arad B	Iaz B	Resita B
Congestion	2339.51	2092.81	2577.79	382.07	382.07	2.19	0.00001	56.24	0
Congestion solved	2382.63	2131.31	2658.64	438.94	427.03	2.24	0.00004	52.96	0.0002
Total [$/h]	26428.41								

4. CONCLUSION

Congestions seem to be the result of regional decisions and priorities enacted separately in each country. Also it can be referred the operational cooperation between territorial operators. System structure plays a positive role in solving the congestion. It is mentioned, availability of generation reserves, respectively the congestion management mechanism chosen. For case study operating condition analysis, the congestion has been solved successfully by changing power flow due to decrease of power consumption and redispatching of generating groups.

The contribution of generators to active power flow is determined in case of considered power losses using Bialek method. MW-km method is used to calculate the transmission costs allocated to generators. Both methods are analyzed using real large scale system, representing the system based on the South-Western side of the Romanian Power System. The computation procedure which combined both methods is easy to implement and presents two main aspects: practicality and precision. Also, the experience of the operator is essential.

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