A new methodology to assign Congestion Costs on Meshed Networks

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Abstract: A new methodology for allocation of congestion costs among market participants which is especially useful for meshed networks is developed in this paper. This method is an alternative to the marginal node tariff method, and has several advantages over it, since it avoids the need to manage the market surpluses that the marginal tariff produces. It also provides economic signals to minimize congestion costs, mitigate the economic consequences of transmission congestion on the revenues of market participants, and palliate eventual attitudes like free riding.

Key-Words: - Transmission charges, Marginal Cost, Congestion charges, transmission losses, Free Access, Transmission Congestion Rights, Free Riding.

1 Introduction

The restructuring of electricity sectors in a great number of countries (e.g. USA, Great Britain, Australia, Argentina, Chile, etc.) during the last few years has brought about the creation of Wholesale Electricity Markets (WEM) which are open to private participation in generation, transmission and distribution activities, with open access to the transmission system.

From the beginning of the operation of these markets, there have been many regulatory problems associated with transmission tariffs, whose origin lies in the theoretical difficulty to apply the marginal theory in the environment of the transmission activity. In search of a better solution to such problems, different methods to calculate transmission charges have been put into practice, each of them with its particular theoretical justification. (see Ref [1], Ref [2], Ref [3]).

In the short run, it is possible to identify at least two cost components in electrical power transmission: i) congestion cost, ii) resistive losses, being the first one the most significant.

One of the basic problems is how to assign congestion costs to market participants in meshed networks. So far, two main methodologies have been put in practice: i) Transmission Congestion Rights **(TCR)**[1]**;** ii) Flow Gates Rights **(FGR)**[2]

This document presents a new methodology to assign congestion costs among market participants, assuming that the market operates within a power pool with or without TCRs, which is especially useful for meshed networks in order to avoid many of the problems that characterize other methods. The document includes a theoretical and conceptual justification with examples of the new proposed methodology.

2 Losses and Congestion Costs

An ideal transmission system is a network that links generators with demands without distorting the economic generation dispatch with the superimposed effect of losses in the circuits and insufficient transmission capacity (congestion).

In such networks, the Short Run Marginal Cost of Energy (SRMgC) at each node of the transmission system (the cost of supplying an additional unit of demand in the node) is the same at all the nodes. In

[1] **Transmission Congestion Rights (TCR):** In this case the holder of the right in a particular circuit obtains the market surpluses that come from this circuit (Difference of energy prices between both ends of the circuit multiplied by the transmitted energy). The rights are usually granted in a public auction where each market participant bids its willingness to pay in advance for such right.

[2] **Flow Gates Rights (FGR):** In this case the holder of the right is compensated with the difference of energy prices between two nodes multiplied by the transmitted energy. To grant such right, mechanisms of public auctions have been created where each market participant indicates the energy to be transported between such nodes and its willingness to pay in advance for such right. The administrator orders the received bids to maximize its revenues verifying that all accepted bids could be satisfied at the same time by the transmission system.

this particular situation, variable transmission costs are equal to zero, so it is possible to define a market price of energy without having to specify the particular node where this price is valid.

If the circuits have losses, as it actually happens in real networks, the SRMgC of each node is not the same, differing in an amount that is proportional to the marginal cost of the losses.

$$\frac{SRMgC_1}{1+\frac{\partial Loss}{\partial d_1}} = \frac{SRMgC_2}{1+\frac{\partial Loss}{\partial d_2}} = ... = \frac{SRMgC_i}{1+\frac{\partial Loss}{\partial d_i}} \quad (1)$$

In a more general case, the economic generation dispatch procedure should take into account the maximum power flow restriction for each circuit as another restriction of the optimization process. If one or more of these restrictions are activated in a particular generation dispatch scenario, then the marginal cost of energy at each node will reflect the congestion cost of the system plus the marginal cost of the losses.

Both effects (losses and congestion), cause generators and consumers that are not in the same node of the transmission system to perceive different energy prices, which actually constitutes an implicit transmission cost that is variable because it depends on the energy flow in the transmission system. Consequently, the energy cost for demand when buying energy at the marginal cost of energy ($Dem), exceeds the total revenues of the generators ($Gen) for selling energy, the difference ($Dem-$Gen) always being positive, and producing a merchandising surplus in the market ($MkS) usually called Tariff Incomes ($TI).

$$\$TI = \sum_i \{(g_i - d_i) \times SRMgC_i\} \geq 0.0 \quad (2)$$

This document develops a methodology to assign $TI among markets participants, with or without TCRs, that is especially useful for meshed networks, producing a merchandising surplus (Market Surplus “$MkS”) equal to zero.

3 Equivalent Network

To solve the above mentioned problem, an equivalent network with the same losses and Tariff Incomes as the real network is developed. The congestion and losses charges that should be paid by market participants in order to obtain a Market surplus equal to zero are then calculated by using the equivalent network.

Equations (3), (4) and (5) show the relationships that allow determining the power flow on each circuit “fk” of a transmission network (linear approximation).

$$f_k = \gamma_k \times (\theta 1_k - \theta 2_k) \quad (3)$$

$$\mathbf{g} - \mathbf{d} = [\boldsymbol{\gamma}] \times \boldsymbol{\theta} \quad (4)$$

$$\boldsymbol{\theta} = [\boldsymbol{\gamma}]^{-1} \times (\mathbf{g} - \mathbf{d}) \quad (5)$$

In order to solve the above system of equations, it is necessary to select a reference node against which the phase angles of the node voltage are measured. Due to this, the square admittance matrix ([Y]) of the network is of dimension N-1, where N is the number of nodes of the network. Vectors **g**, **d**, and θ also have dimension N-1.

It is also possible to determine the power flow by using the so-called **Indefinite Admittance Matrix [YI]** of the network. The matrix [YI] is a square matrix of dimension **N**. Construction of the [YI] matrix is similar to that of the [Y] matrix, but without any reference node. The resulting [YI] matrix satisfies the condition that the sum of all elements of rows and columns be null.

The [YI] matrix determines the relationships between demand and generation in each node, and the phase angles of the node voltage θ, which is measured against an ***indefinite*** node that is not part of the transmission network. In this case, vectors **g**, **d**, and θ have dimension N.

$$\mathbf{g} - \mathbf{d} = [\gamma_I] \times \boldsymbol{\theta} \quad (6)$$

There is a lineal dependence in the above system of equations that makes it impossible to obtain the inverse of the [YI] matrix, due to the fact that an equation may be obtained as a lineal combination of the remaining ones.

It is possible to solve this problem by making the following approximation:

$$[\gamma_I] \cong [\gamma_S] \quad (7)$$

where

$$\gamma_S(i,i) = \gamma_I(i,i) \times (1+h) \quad (8)$$

with h equal to a real constant: **h<<1.0**

$$\gamma_S(j,i) = \gamma_I(j,i) \text{ ; for j<>I} \quad (9)$$

Now, it is possible to determine the inverse of the ([YS]) matrix since the attaché of the factor (1+h) in the self coefficients of the matrix will prevent their determinant from being null.

By using the $[YS]^{-1}$ matrix, it is possible to determine the power flow.

$$\boldsymbol{\theta} = \{[\gamma_S]^{-1} \times (\mathbf{g} - \mathbf{d})\} \mod \pm\pi \quad (10)$$

$$f_k = \gamma_{Sk} \times (\theta 1_k - \theta 2_k) \quad (11)$$

The above calculus procedure produces an exact result in terms of power flows in the network, without the need to define a particular node of the transmission system as a reference node.

The $[YS]^{-1}$ matrix tends to infinite when the constant "h" tends to zero, but the phase angle of the node voltages against the "indefinite reference" will be limited to the range ±π, thus the difference (θ1k - θ2k) will always be a finite value, which only depends on the topology of the network and on the admittance of each circuit.

To calculate the power flows in each circuit, it is useful to determine the so-called **Beta (ß) matrix** of the network[3]. Each element of the **(ß)** matrix determines the relationship between the power flow in each circuit and the net power injection in each node.

$$\beta_{ki} = \frac{\Delta f_k}{\Delta g_i} \quad (12)$$

Note that the use of $[Ys]^{-1}$ matrix to calculate the power flow and the **(ß) matrix** makes it unnecessary to specify a particular node of the real network in which Δgi is compensated.

With **(ß) matrix** it is possible to calculate the power flow in each circuit (fk) of the transmission network by using the following formula.

$$f_k = \sum_i \{\beta_{ki} \times (g_i - d_i - loss_i)\} \quad (13)$$

$$loss_i = \frac{1}{2} \times \sum_j \{\frac{r_j}{Pb} \times f_j \times \sum_i [\beta_{ji} \times (g_i - d_i)]\} \quad (14)$$

$$\sum_i g_i = \sum_i d_i + \sum_i loss_i \quad (15)$$

Note: Equations (13), (14) and (15) have a mutual dependence, so they must be solved sequentially until the convergence is reached.

[3] In **Ref. [4]**, a simple procedure is shown to calculate the **(ß)** matrix.

The Tariff Incomes ($TI) resulting from congestion and losses on the network can be obtained from the following formulas:

$$\$TI = \sum_i \{(g_i - d_i) \times SRMgC_i\} = \sum_k \{f_k \times \Delta SRMgC_k\} \quad (16)$$

$$\$TI = \sum_k \{\Delta SRMgC_k \times \sum_i [\beta_{ki} \times (g_i - d_i)]\} - loss \times SMgC \quad (17)$$

$$SMgC = SRMgC_i - \sum_k \{\beta_{ki} \times \Delta SRMgC_k\} \quad (18)$$

$$SMgC = SRMgC_i - TMgC_i \quad (19)$$

Equation (19) shows that the energy marginal cost of each node of the transmission network (SRMgCi) is equal to the addition of two terms: one of them, **SMgC**, is a common value for the whole market while the TMgCi is a different value for each node.

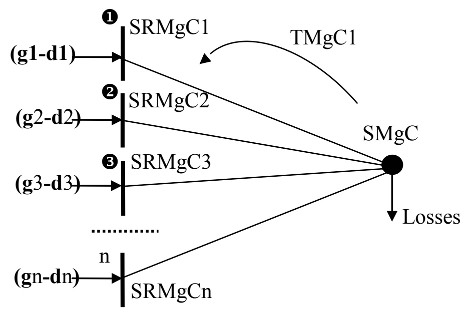
Equations (16) to (19) can be reorganized as follows:

$$\$TI = \sum_i \{(g_i - d_i) \times (SMgC + TMgC_i)\} \quad (20)$$

$$\$TI = SMgC \times Losses + \sum_i \{(g_i - d_i) \times TMgC_i)\} \quad (21)$$

$$TMgC_i = \sum_k \{\beta_{ki} \times \Delta SRMgC_k\} \quad (22)$$

Equation (21) allows us to define an "**equivalent network**" from a real generic network with N nodes, whose topological representation is shown in the next figure.



The proposed equivalent network has the following properties:

- It has N+1 nodes, where N is the number of nodes on the real network, with a radial topology where each circuit of the equivalent network links each node on the real network with a new node called Market Node (**M**)[4].

[4] It can be demonstrated that the Market node "**M**" is located in the "*electric barycenter*" of the transmission network.

- Its Admittance Matrix is diagonal (all mutual components are null), meaning that there is no coupling between nodes.
- It has the same losses and Tariff Incomes as the real network.
- Losses are concentrated on the Market Node, allowing for generation / demand balance.
- From the point of view of generators and demands, there is no difference between the real network and the equivalent network.
- No node on the real network is considered as a preferential node or reference node.

In this "equivalent network" generators and demands buy and sell energy at the marginal cost of the system (SMgC), and pay, at the same time, the transmission marginal cost of each node (TMgCi).

$$\$Gi = g_i \times SRMgC_i = g_i \times (SMgC + TMgC_i) \quad (23)$$

$$\$Di = -d_i \times SRMgC_i = -d_i \times (SMgC + TMgC_i) \quad (24)$$

The model also allows identifying the proportion of the total losses produced by each market participant by using the following equations:

$$lossG_i = g_i \times \sum_k (\frac{r_k}{Pb} \times f_k \times \beta_{ki}) \quad (25)$$

$$lossD_i = -d_i \times \sum_k (\frac{r_k}{Pb} \times f_k \times \beta_{ki}) \quad (26)$$

4 Market Surplus ($MkS) allocation

The theoretical aspects developed in the previous points allow identifying the participation of each market participant in the Tariff Incomes originated by losses and congestion.

The transmission marginal cost of each node (TMgCi) can be split into two components: Positive components ($PTMgCi) are charges that must be paid by market participants. Negative components ($NTMgCi) are transmission revenues that market participants receive, due to the aggregated effect of congestion and losses.

$$TMgC_i = \sum_k \{PTMgC_{ki} + NTMgC_{ki}\} \quad (27)$$

$$PTMgC_{ki} = \beta_{ki}(+) \times \Delta SRMgC_k(+) + \beta_{ki}(-) \times \Delta SRMgC_k(-) \quad (28)$$

$$NTMgC_{ki} = \beta_{ki}(+) \times \Delta SRMgC_k(-) + \beta_{ki}(-) \times \Delta SRMgC_k(+) \quad (29)$$

Note: The identification of the positive and negative components of the transmission marginal cost is possible because the transmission cost was segregated from the energy marginal cost of the system.

To make the market surplus ($MkS) equal to zero ($MkS=0.0), the Tariff Incomes ($TI) net of TCR´s payments should return ($TI - TCR´s) to market participants through a new transmission charge called "Transmission Incomes Reimbursement ($TIR)", which, for a particular market participant, could be a positive or negative value.

$$\$MkS = 0.0 = \$TI - \$TTCR + \$TTIR \quad (30)$$

$$\$TTIR = \sum_i \{\$GTIR_i + \$DTIR_i\} \quad (31)$$

$$\$TTCR = \sum_k \{\$TCR_k\} \quad (32)$$

$$\$GTIR_i = g_i \times \left(TMgC_i - \sum_k \{TCCG_k\} \right) \quad (33)$$

$$\$DTIR_i = -d_i \times \left(TMgC_i - \sum_k \{TCCD_k\} \right) \quad (34)$$

For circuit "k" where TCR´s were granted

$$TCCG_k = PTMgC_{ki} + NTMgC_{ki} \quad (35)$$

$$TCCD_k = PTMgC_{ki} + NTMgC_{ki} \quad (36)$$

$$\$TCR_k = 0.0 \quad (37)$$

For circuit "k" where no TCR´s were granted.

$$TCCG_k = H_k \times PTMgC_{ki} + NTMgC_{ki} + + SMgC \times rpu_k \times \beta_{ki} \times f_k \quad (37)$$

$$TCCD_k = PTMgC_{ki} + H_k \times NTMgC_{ki} + + SMgC \times rpu_k \times \beta_{ki} \times f_k \quad (38)$$

$$H_k = -\frac{\$TE_k}{\$TC_k} \leq 1.0 \quad (39)$$

$$\$TE_k = \sum_i \{g_i \times PTMgC_{ki}\} - \sum_i \{d_i \times NTMgC_{ki}\} \quad (40)$$

$$\$TC_k = \sum_i \{g_i \times NTMgC_{ki}\} - \sum_i \{d_i \times PTMgC_{ki}\} \quad (41)$$

$$\$TCR_k = \sum_i \{(g_i - d_i) \times \Delta SRMgC_k \times \beta_{ki}\} + \\ - \sum_i \{SMgC \times (lossG_{ki} + lossD_{ki}\} \quad (42)$$

If Hk is bigger than 1.0 there will be a market surplus (\$MkS≠0.0) meaning that for circuit "k" there are no market participants that have the obligation to pay the full transmission congestion cost of such circuit. In this case one possibility to attain \$MkS=0.0 is assigning the market surplus to all market participants with net resulting (sell / buy) energy price different from the SRMgC of its node, proportionally to such difference.

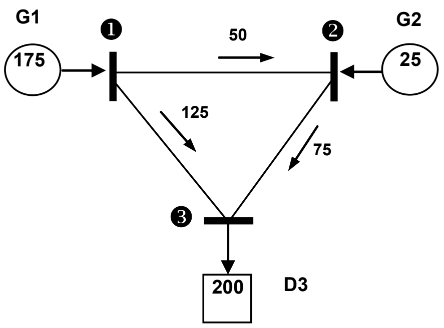
5 Examples

Following two examples are presented where all the previously developed theoretical concepts are applied.

5.1 A classical example

For illustrative purposes, next figure shows a simple network with three interconnected nodes.

Actual network



Node 1 and Node 2 are generation nodes which have G1=G2=200 MW available generation with a marginal cost of 10 \$/MW and 30\$/MW, respectively.

Node 3 is a demand node which has a total demand of 200 MW.

The three interconnection lines have the same electrical data (line impedance) with no transmission losses (negligible). Line (1-2) has a transmission capacity of 50 MW. Lines (1-3) and (2-3) have a transmission capacity of 200 MW.

The above figure shows a minimum cost generation dispatch that fulfills all transmission constraints. Due to transmission constraints on line (1-2), G1 (the cheapest generation) cannot supply all the demand. It is necessary that G2=25 MW to supply the demand and consequently G1 has to reduce its dispatch to 175 MW.

Beta (ß) matrix
(using indefinite admittance matrix)

Circuit	Node		
	1	2	3
1-2	0.33333	-0.33333	0.00000
1-3	0.33333	0.00000	-0.33333
2-3	0.00000	0.33333	-0.33333

The SRMgC at node 1 is equal to the incremental cost of the system to supply 1 MW of additional demand at node 1. Since G1 is not fully dispatched and it is the cheapest generation, the SRMgC at node 1 is equal to the marginal cost of G1 (10 \$/MW).

The incremental cost of the system at node 2 is not the same. If we consider 1 MW of additional demand at node 2 it cannot be supplied from G1 due to transmission constraints in line (1-2). Instead, the additional demand should be supplied by G2 since it is not fully dispatched and G2 it is not affected by a line constraint. Then, the SRMgC at node 2 is equal to the marginal cost of G2 (30 \$/MW).

To supply 1 MW additional demand at node 3 it is necessary to increase the dispatch of both G1 and G2 (1/2 MW each one) due to the transmission constraint in line 1-2. Then, the SRMgC at node 3 is equal to the average marginal cost of G1 and G2 (20 \$/MW).

The congestion cost of a particular line is equal to the difference of SRMgC between end nodes of the line multiplied by its power flow (i.e. Congestion cost of line 1-2 is equal to ((30-10)\$/MW x 50MW = 1000\$).

Note that:

- For a particular line, congestion cost may be a positive o negative value.
- Even when there is only one active line constraint (line 1-2), the SRMgC at all nodes are different and then there are congestion costs in all lines (this is a characteristic of meshed networks).

Marginal Costs

Marginal Cost (\$/MW)	Node		
	1	2	3
SRMgC	10.00	30.00	20.00
TMgC	**10.00**	**-10.00**	**0.00**
SMgC	**20.00**		

Congestion Costs

Circuit	TOTAL ($)
1-2	1000.0
1-3	1250.0
2-3	-750.0
TOTAL	1500.0

If TCRs were not granted for any lines, the Market Surplus is equal to the Total Congestion Cost (1500 $).

If we include Transmission Incomes Reimbursement ($TIR) the market balance result is as follows.

Market Balance (Without TCRs)

Market Balance ($)	Node			TOTAL
	1	2	3	
Sell (Generation)	1750.0	750.0	0.0	2500.0
$TIR (Generation)	1055.6	0.0	0.0	1055.6
Buy (Demand)	0.0	0.0	-4000.0	-4000.0
$TIR (Demand)	0.0	0.0	444.4	444.4
$TCR				0.0
Market Surplus				0.0

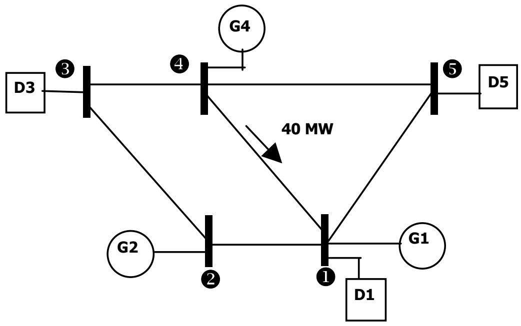
Generation / Demand Net Results

Total ($/MW) Buy/Sell price	Node		
	1	2	3
Generation	16.03	30.00	-
Demand	-	-	17.78

5.2 Complex network with congestion and losses

Next example shows the same concepts of the previous example applied to a complex transmission network with losses and constraints and multiple generation and demand nodes.

Actual network



Data:

All circuits have a reactance equal to 1pu and losses factor of 10%

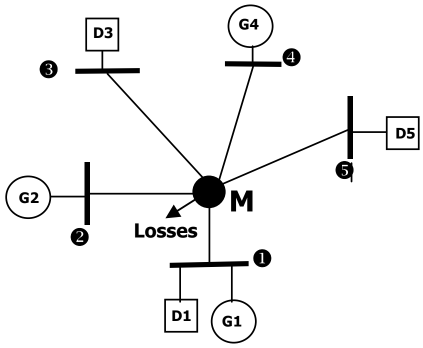
G1 max=50 MW (@50$/MW);
G2 max= 50 MW (@20$/MW);
G4 max=100 MW (@15$/MW);
D1=120 MW; D3=10 MW; D5=40 MW
Transmission capacity:
P(4-1) (MAX) = 40 MW

Results:

(from the economic minimum cost generation dispatch)

Generation Dispatch (MW)
G1 = 39.4; G2 = 50.0; G4=85.7
Losses (MW) = 5.1
Power Flow (MW) (at circuit center)
(2-1): 42.7; (2-3): 6.4; (4-3): 3.7
(4-1): 40.0; (4-5): 40.4 (1-5): 0.4

Equivalent network



Indefinite Admittance Matrix (Y_I) (real network)

Node	1	2	3	4	5
1	3.0000	-1.0000	0.0000	-1.0000	-1.0000
2	-1.0000	2.0000	-1.0000	0.0000	0.0000
3	0.0000	-1.0000	2.0000	-1.0000	0.0000
4	-1.0000	0.0000	-1.0000	3.0000	-1.0000
5	-1.0000	0.0000	0.0000	-1.0000	2.0000

Beta (ß) Matrix

Circuit	Node				
	1	2	3	4	5
1-2	0.25758	-0.46970	-0.19697	0.07576	0.16667
1-4	0.27273	0.09091	-0.09091	-0.27273	0.00000
1-5	0.21970	0.12879	0.03788	-0.05303	-0.41667
2-3	0.09091	0.36364	-0.36364	-0.09091	0.00000
3-4	-0.07576	0.19697	0.46970	-0.25758	-0.16667
4-5	-0.05303	0.03788	0.12879	0.21970	-0.41667

Losses Balance

Losses (MW)	Nodo					TOTAL
	1	2	3	4	5	
Loss G	-0.91	0.98	0.00	1.45	0.00	1.52
Loss D	2.77	0.00	-0.13	0.00	0.94	3.58
TOTAL	1.86	0.98	-0.13	1.45	0.94	5.10

Transmission Cost

Losses plus Congestion cost	Cost [$]
Circuit	
1-2	543.8
1-4	1345.3
1-5	-7.8
2-3	-69.3
3-4	43.8
4-5	694.6
TOTAL	2550.4

Marginal Cost

Marginal Cost ($/MW)	Node				
	1	2	3	4	5
SRMgC	50.00	35.82	25.68	15.00	33.50
TMgC	**-17.92**	**-3.74**	**6.40**	**17.08**	**-1.42**
SMgC	**32.08**				

PTMgC	Node				
Circuit	1	2	3	4	5
1-2	0.00	6.66	2.79	0.00	0.00
1-4	0.00	0.00	3.18	9.55	0.00
1-5	0.00	0.00	0.00	0.87	6.88
2-3	0.00	0.00	3.69	0.92	0.00
3-4	0.81	0.00	0.00	2.75	1.78
4-5	0.00	0.70	2.38	4.06	0.00
NTMgC	**Node**				
Circuit	1	2	3	4	5
1-2	-3.65	0.00	0.00	-1.07	-2.36
1-4	-9.55	-3.18	0.00	0.00	0.00
1-5	-3.62	-2.13	-0.63	0.00	0.00
2-3	-0.92	-3.69	0.00	0.00	0.00
3-4	0.00	-2.10	-5.02	0.00	0.00
4-5	-0.98	0.00	0.00	0.00	-7.71
TMgC [$/MW]	**-17.92**	**-3.74**	**6.40**	**17.08**	**-1.42**

Market Balance

Case A): Without TIRs and TCRs

Market Balance ($)	Node					TOTAL
	1	2	3	4	5	
Sell (Generation)	1970.0	1791.0	0.0	1285.5	0.0	5046.5
Buy (Demand)	-6000.1	0.0	-256.8	0.0	-1340.0	-7596.9
Market Surplus						**2550.4**

Case B): With TIRs, Without TCRs

Market Balance ($)	Node					TOTAL
	1	2	3	4	5	
Sell (Generation)	1970.0	1791.0	0.0	1285.5	0.0	5046.5
$TIR (Generation)	33.7	232.4	0.0	860.2	0.0	1126.3
Buy (Demand)	-6000.1	0.0	-256.8	0.0	-1340.0	-7596.9
$TIR (Demand)	1092.8	0.0	11.1	0.0	320.1	1424.1
$TCR						0.0
Market Surplus						**0.0**

Case C): With TIRs and TCRs in all circuits

Market Balance ($)	Node					TOTAL
	1	2	3	4	5	
Sell (Generation)	1970.0	1791.0	0.0	1285.5	0.0	5046.5
$TIR (Generation)	0.0	0.0	0.0	0.0	0.0	0.0
Buy (Demand)	-6000.1	0.0	-256.8	0.0	-1340.0	-7596.9
$TIR (Demand)	0.0	0.0	0.0	0.0	0.0	0.0
$TCR						2550.4
Market Surplus						**0.0**

Case D): With TIRs and TCRs only in circuit (1-4)

Market Balance ($)	Node					TOTAL
	1	2	3	4	5	
Sell (Generation)	1970.0	1791.0	0.0	1285.5	0.0	5046.5
$TIR (Generation)	19.9	226.6	0.0	308.4	0.0	554.9
Buy (Demand)	-6000.1	0.0	-256.8	0.0	-1340.0	-7596.9
$TIR (Demand)	320.2	0.0	10.0	0.0	320.1	650.2
$TCR						1345.3
Market Surplus						**0.0**

Generation / Demand Net Result (total buy/sell prices)

Generation ($/MW)	Node				
	1	2	3	4	5
Case A	50.00	35.82	-	15.00	-
Case B	50.85	40.47	-	25.04	-
Case C	50.00	35.82	-	15.00	-
Case D	50.50	40.35	-	18.60	-

Demand ($/MW)	Node				
	1	2	3	4	5
Case A	50.00	-	25.68	-	33.50
Case B	40.89	-	24.57	-	25.50
Case C	50.00	-	25.68	-	33.50
Case D	47.33	-	24.68	-	25.50

5.3 Remarks

The following properties of the new proposed methodology can be identified from the above results:

- The revenue of generators, net of transmission charges (losses and congestion), is equal to or higher than the revenue that would be obtained if the generators were compensated with the short run marginal cost of the nodes where they are is connected to the transmission system.
- The total supply cost for any demand is equal to or lower than the cost that would be obtained if demand bought energy at the short run marginal cost of each node.
- The market surplus is equal to zero with or without TCRs.
- The marginal power plant revenue is equal to or higher than its variable cost.
- Generators and Demands located in the same node may not perceive the same energy price (net).

6…Conclusion

A methodology for allocation of congestion costs among market participants has been developed in a theoretical and conceptual way, aiming to promote efficiency in the operation of the electricity markets and, at the same time, fulfilling the following objectives:

Sufficiency: There is no Market surplus from congestion and losses.

Fairness: Transmission Charges paid by Demands and Generators are determined with similar methodologies.

Symmetry: There are no preferential nodes.

Globalization: The methodology could be applied both for bilateral transactions and in the spot market.

Transparency: Transmission congestion charges are obtained separately from the marginal cost of energy.

The proposed methodology determines explicit transmission charges that allow it to cover all variable costs of the transmission system by using the marginal cost of energy at each node of the transmission system obtained from the economic generation dispatch.

The resulting transmission charges do not produce the market surpluses that characterize marginal node prices. This increases the remuneration of the generators, net of transmission charges and, at the same time, decreases the net purchase cost of the demands, net of transmission charges,

The transmission charges also ensure that all generators obtain a marginal revenue for energy when their production is affected by a congestion of the transmission system. Similarly, the transmission charges allow demands to reduce the energy purchasing cost when the marginal generator is located in their node.

If the regulatory framework of the market has created the TCRs figure, the new model allows us to cover the congestion risk and, at the same time, mitigate behaviors like free riding that have often prevented the normal expansion of the transmission system under private risk.

7 Glossary

i: Each node of the network
j: each node linked with node i
k: Each circuits of the network
γk [pu]: Admittance of the circuit k
$\theta 1k$ - $\theta 2k$: Angle of phase of the node voltage between both ends of the circuit k;
g, **d** [MW]: Generation and Demand vectors
[Y] [pu]: Admittance matrix
$[\mathbf{Y}]^{-1}$: Inverse of the Admittance matrix
$\boldsymbol{\theta}$: Vector of phase angles of the node voltages
fk [MW]: Power Flow in the circuit k.
rk [pu]: resistance of the circuit k
Pb [MW] Base Power used to calculated resistances and reactance of the network.
SRMgCi [$/MW]: Short Run Marginal Cost at node i
ΔSRMgCk [$/MW]: Difference between energy marginal costs at both end of the circuit k.
SMgC [$/MW]: System Marginal Cost
TMgCi [$/MW]: Transmission Marginal Cost of node i
PTMgCi [$/MW]: Positive Transmission Marginal Cost of node i
NMgCi [$/MW]: Negative Transmission Marginal Cost of node i
lossGi [MW]: Losses produced by the generators located in node i
lossDi [MW] losses produced by the demands located in node i
gi, di [MW] generation and demand at node i
[YI] [pu]: Indefinite Admittance matrix
βki : Cœfficient of beta matrix
$MKS [$]: Market surplus

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