Towards a Cost Reflective Tariff for Distribution Networks: The Effect of DG

Paul M. Sotkiewicz and J. Mario Vignolo, *Member, IEEE**

***Abstract*— This paper follows up on its companion paper decomposing the effects of the transition from a fully average cost distribution tariff to a cost reflective distribution tariff, in terms of time and location, that uses nodal prices to recover losses and an "extent-of-use" method to recover network fixed costs based on use at coincident peak, but in the presence of distributed generation (DG).**

As we do in the companion paper, we apply our tariff transition and decomposition method to an example network with data from Uruguay to isolate the various effects including the influence of DG.

***Index Terms*— Distribution networks, tariffs, loss allocations, fixed cost allocations, distributed generation.**

I. INTRODUCTION

IN the companion paper to this work [4] we examined the changes in distribution charges attributable to moving from a tariff that averages the cost of losses and network fixed costs over all load to a cost-reflective tariff that uses nodal pricing to recover the cost of losses as suggested in [3] and the Amp-mile Method as proposed in [2] that recovers network fixed costs through a locational charge based on the "extent of use" at the coincident peak. We decomposed the change into four components: Changes due to use at coincident peak for network costs; changes due to charging by location (extent of use) for network costs; changes due to moving to marginal losses under nodal pricing while respecting the constraint that we cannot recover more than the cost of losses (reconciliated marginal losses); and the change due to moving to full marginal losses under nodal pricing and using the merchandising surplus to offset network charges so we respect the constraint that we cannot over-recover for the costs of the system.

We showed moving to coincident peak charges and to fully charging for marginal losses while rebating the merchandising surplus through the fixed charges have the greatest effects on changes in distribution tariff charges with each of these effects acting as a counterbalance to the other. In our example the coincident peak effect dominated the locational effect leading to the counter-intuitive result that loads far from the interface with transmission (power supply point) actually paid lower charges under the cost reflective tariff than previously. Surprisingly, the incremental movements to extent-of-use locational charges and reconciliated marginal losses had only small effects by comparison. Such results support the necessity of analyzing the decomposition of tariff changes to fully understand the reasons for the direction and magnitude of changes in tariff charges in the transition to more cost-reflective tariffs.

In this paper we introduce distributed generation (DG) into the analysis following up on [3] and [2] and the companion paper [4]. DG is important in that, if located optimally, it can reduce line losses and effectively create additional distribution capacity at the coincident peak. As argued in [3] and [2], DG should be compensated for reducing losses by being paid at nodal prices and being paid for the capacity created under the Amp-mile Method. Thus, DG provides countervailing cost changes to distribution tariffs for loads. By reducing line losses, DG has the ability to reduce the loss component of the distribution tariff. However, if it is paid for the capacity it creates, the load has a larger network fixed cost for which it must pay. The effect that dominates for loads of a particular profile and location is analytically unclear, indicating the need for simulation analysis.

In Sections II and III we outline the various methods for recovering losses and network fixed costs necessary for our comparison and decomposition. Section IV describes our results both analytically, to the extent possible, and of our simulation exercise, and Section V concludes.

II. DISTRIBUTION TARIFF LOSSES AND DISTRIBUTED GENERATION REVENUES

For use in this section and subsequent sections we define the following notation.

Let k be the index of busses on the distribution network with $k = 1, ..., n$.

Let $k = 0$ be the reference bus and this is also the power supply point (PSP) for the distribution network.

Let t be the index of time with $t = 1, ..., T$.

Let subscripts d and g represent demand and generation.

Let P_{dtk} and P_{gtk} be the active power withdrawal and injection respectively at node k at time t.

Let Q_{dtk} and Q_{gtk} be the reactive power withdrawal and injection respectively at node k at time t.

Let P_{t0} be the active power injected at the reference bus at time t.

Let λ_t be the price of power at the reference bus at time t.

Let $Loss_t$ be the line losses at time t.

A. Average Losses

Just as we defined the charges to load at bus k for average losses in [4] we re-state that here.

* Vignolo is with Instituto de Ingeniería Eléctrica, Universidad de la República , Montevideo, Uruguay. Sotkiewicz with the Public Utility Research Center and Department of Economics, University of Florida, Gainesville, Florida USA. (Email: jesus@fing.edu.uy; paul.sotkiewicz@cba.ufl.edu)

$$AL_{dk} = \frac{\sum_{t=1}^{T} P_{dtk}}{\sum_{t=1}^{T}\sum_{k=1}^{n} P_{dtk}} \sum_{t=1}^{T} Loss_t \lambda_t, \qquad (1)$$

We follow the practice in Uruguay for any distributed generation sources connected to the system and assume they are not charged for losses. However, DG still collects revenue from selling power and is paid the prices at the PSP, λ_t each period it runs. The total revenue stream is then

$$\sum_{t=1}^{T} P_{gtk}\lambda_t \qquad (2)$$

B. Marginal Losses from Nodal Prices

We define nodal prices just as we did in [4], but relative to withdrawals at node k:

$$pa_{tk} = \lambda_t(1 + \frac{\partial Loss_t}{\partial P_{dtk}}) \qquad (3)$$

$$pr_{tk} = \lambda_t(\frac{\partial Loss_t}{\partial Q_{dtk}}), \qquad (4)$$

where the price of reactive power at the reference bus is assumed to be zero. The charge for marginal losses for loads at bus k is

$$ML_{dk} = \sum_{t=1}^{T} \lambda_t(\frac{\partial Loss_t}{\partial P_{dtk}})P_{dtk} + \lambda_t(\frac{\partial Loss_t}{\partial Q_{dtk}})Q_{dtk}. \qquad (5)$$

Under nodal pricing distributed generation connected to the network is paid the nodal price including marginal losses. The revenue collected by distributed generation at bus k is

$$REV_{gk}^{ML} = \sum_{t=1}^{T} \lambda_t(1 + \frac{\partial Loss_t}{\partial P_{dtk}})P_{gtk} + \lambda_t(\frac{\partial Loss_t}{\partial Q_{dtk}})Q_{gtk}. \qquad (6)$$

The distribution company recovers energy costs inclusive of losses plus a merchandising surplus over all hours t (*MS*) equal to:

$$MS = \sum_{t=1}^{T}\sum_{k=1}^{n} pa_{tk}(P_{dtk} - P_{gtk}) + pr_{tk}(Q_{dtk} - Q_{gtk}) - \sum_{t=1}^{T} \lambda_t P_{t0} \qquad (7)$$

$$MS = \sum_{t=1}^{T}\sum_{k=1}^{n} \lambda_t[(1 + \frac{\partial Loss_t}{\partial P_{dtk}})(P_{dtk} - P_{gtk}) + (\frac{\partial Loss_t}{\partial Q_{dtk}})(Q_{dtk} - Q_{gtk})] - \sum_{t=1}^{T} \lambda_t P_{t0}. \qquad (8)$$

And we note that in general, the merchandising surplus is greater than zero.

C. Reconciliated Marginal Losses

We follow the same method for reconciliated marginal losses as we did in [4] and follow [1]. Again, reconciliated marginal losses adjust the marginal loss coefficients so that the nodal prices exactly cover the cost of losses.

Consider the approximation of losses, $ALoss_t$

$$ALoss_t = \sum_{k=1}^{n} \frac{\partial Loss}{\partial P_{dtk}} P_{dtk} + \frac{\partial Loss}{\partial Q_{dtk}} Q_{dtk} + \frac{\partial Loss}{\partial P_{gtk}} P_{gtk} + \frac{\partial Loss}{\partial Q_{gtk}} Q_{gtk}, \qquad (9)$$

noting that the marginal loss coefficient for injections ($\frac{\partial Loss}{\partial P_{gtk}}$ and $\frac{\partial Loss}{\partial Q_{gtk}}$) have the opposite sign of the marginal loss coefficients for withdrawals.

Dividing the actual losses by the approximation of losses provides the reconciliation factor in period t, RF_t.

$$RF_t = \frac{Loss_t}{ALoss_t} \qquad (10)$$

We can then compute reconciliated prices, similar to the prices in equations (3) and (4), but with the marginal loss factors multiplied by the reconciliation factor and the resulting loss charges for load at time t for bus k.

$$pa_{tk}^r = \lambda_t(1 + RF_t\frac{\partial Loss_t}{\partial P_{dtk}}) \qquad (11)$$

$$pr_{tk}^r = \lambda_t(RF_t\frac{\partial Loss_t}{\partial Q_{dtk}}), \qquad (12)$$

$$RL_{dk} = \sum_{t=1}^{T} \lambda_t RF_t(\frac{\partial Loss_t}{\partial P_{dtk}} P_{dtk} + \frac{\partial Loss_t}{\partial Q_{dtk}} Q_{dtk}) \qquad (13)$$

Under reconciliated nodal pricing distributed generation connected to the network is paid the nodal price including marginal losses. The revenue collected by distributed generation at bus k is

$$REV_{gk}^{RL} = \sum_{t=1}^{T} \lambda_t(1 + RF_t\frac{\partial Loss_t}{\partial P_{dtk}})P_{gtk} + \lambda_t(RF_t\frac{\partial Loss_t}{\partial Q_{dtk}})Q_{gtk}. \qquad (14)$$

The resulting reconciliated merchandising surplus is equal to zero by construction.

$$MS^r = \sum_{t=1}^{T}\sum_{k=1}^{n} pa_k^r(P_{dtk} - P_{gtk}) + pr_{tk}^r(Q_{dtk} - Q_{gtk}) - \sum_{t=1}^{T} \lambda_t P_{t0} \qquad (15)$$

$$MS^r = \sum_{t=1}^{T}\sum_{k=1}^{n} \lambda_t[(1 + RF_t\frac{\partial Loss_t}{\partial P_{dtk}})(P_{dtk} - P_{gtk}) + RF_t(\frac{\partial Loss_t}{\partial Q_{dtk}})(Q_{dtk} - Q_{gtk})] - \sum_{t=1}^{T} \lambda_t P_{t0}$$

$$= \sum_{t=1}^{T}\sum_{k=1}^{n}\lambda_t(P_{dtk} - P_{gtk} + Loss_t) - \sum_{t=1}^{T}\lambda_t P_{t0} = 0 \quad (16)$$

III. Distribution Tariffs: Capital and Non-variable O & M Costs

As in the previous section, we follow the companion paper to this work [4]. For this section, we define the following additional variables that will be used throughout the remainder of this section.
Let l be the index of circuits with $l = 1, ..., L$.
Let CC_l be the levelized capital and non-variable O & M cost or fixed cost of circuit l.
Let I_l^{peak} be the current flow through circuit l at the coincident peak.
Let CAP_l be the capacity of circuit l.
Let $peak$ as a superscript denote values at the coincident peak.

A. Per MWh Average Charges

Following the tariff from [4], we define the charge for loads at each bus for the recovery of network costs as

$$NAC_{dk} = \frac{\sum_{t=1}^{T} P_{dtk}}{\sum_{t=1}^{T}\sum_{k=1}^{n} P_{dtk}} \sum_{l=1}^{L} CC_l. \quad (17)$$

Following the regulatory practice in Uruguay, distributed generation resources do not face fixed network charges.

B. Coincident Peak Charges

Again, following the same tariff from [4] the charge for loads at each bus for the recovery of network charges at coincident peak is

$$NPC_{dk} = \frac{P_{dk}^{peak}}{\sum_{k=1}^{n} P_{dk}^{peak}} \sum_{l=1}^{L} CC_l. \quad (18)$$

We assume once again that distributed generation does not face fixed network charges under this tariff scheme as would be regulatory practice in Uruguay.

C. Locational Peak Charges: Amp-mile

We refer the reader to the companion paper [4] and to [2] for discussion about the Amp-mile method. We adjust and define the notation needed for Amp-mile in the presence of distributed generation.

We do remind the reader the fixed charge computed under amp-mile has two parts. The first part is based on the extent of use of all circuits by loads at each bus at the system coincident peak (locational portion) for only the portion of the circuit capacity that is used. The second part of the charge covers costs associated with the unused portion of the circuit capacity and is recovered over all load at coincident peak. Thus, the mechanism has the property that when the circuit is at capacity, all costs for that circuit are recovered through locational charges. When the circuit is relatively unloaded, the majority of costs will be recovered over all load at peak.

We define the active and reactive power to absolute current distribution factors with respect to an injection or withdrawal at bus k to the absolute value of current on the line l, at the coincident peak as:

$$APIDF_{ilk}^{peak} = \frac{\partial I_l^{peak}}{\partial P_{ik}^{peak}} \quad (19)$$

$$RPIDF_{ilk}^{peak} = \frac{\partial I_l^{peak}}{\partial Q_{ik}^{peak}}, \quad (20)$$

where $i \in \{d, g\}$. We note that the $APIDF$ and $RPIDF$ may have the opposite sign for injections from DG resources connected to the system.

We can then define the active and reactive power extent of use factors of circuit l for load and/or generation at bus k respectively as

$$AEoUL_{ilk}^{peak} = \frac{APIDF_{ilk}^{peak} \times P_{ik}^{peak}}{AI_l^{peak}} \quad (21)$$

$$REoUL_{ilk}^{peak} = \frac{RPIDF_{ilk}^{peak} \times Q_{ik}^{peak}}{AI_l^{peak}}, \quad (22)$$

where $i \in \{d, g\}$ and AI_l^{peak} is a scaling factor defined so that the summation for all busses for a given line l equals one.

$$AI_l^{peak} = \sum_{k=1}^{n} APIDF_{dlk}^{peak} P_{dk}^{peak} + RPIDF_{dlk}^{peak} Q_{dk}^{peak} + APIDF_{glk}^{peak} P_{gk}^{peak} + RPIDF_{glk}^{peak} Q_{gk}^{peak} \quad (23)$$

Again, because the $APIDF$ and $RPIDF$ may have opposite signs for DG resources, the extent of uses factors defined in (21) and (22) may also be negative which has implication for the charges defined below in (25) and (26).

Define the adapted or used circuit capacity for the levelized annual circuit cost to be recovered through locational charges as of

$$ACC_l^{peak} = \frac{I_l^{peak}}{CAP_l} \times CC_l, \quad (24)$$

Thus, the locational charges to load and generation for active and reactive power are

$$AL_{ik}^{peak} = \sum_{l=1}^{L} AEoUL_{ilk}^{peak} \times ACC_l^{peak} \quad (25)$$

$$RL_{ik}^{peak} = \sum_{l=1}^{L} REoUL_{ilk}^{peak} \times ACC_l^{peak} \quad (26)$$

where $i \in \{d, g\}$.

As intimated above, it should be noted that for distributed generation connected to the network, it is possible that the locational charge is negative, thus distributed generation is paid for providing counterflow that essentially creates capacity *on the network. This will only happen if the DG resource locates so that it reduces current flow on a circuit. If the charge is negative, it creates another revenue stream for DG resources.*

Again, the extent of use method we use will not allocate all fixed costs based upon the extent of use. The remaining non-locational costs that must be covered are

$$RCC^{peak} = \sum_{l=1}^{L}(CC_l - ACC_l^{peak}), \tag{27}$$

and these costs will be allocated based on the individual loads, *not to generation*, at the coincident peak as a non-locational charge NL_{dk}^{peak}.

$$NL_{dk}^{peak} = \frac{P_{dk}^{peak}}{\sum_{k=1}^{n} P_{dk}^{peak}} RCC^{peak}. \tag{28}$$

IV. Tariff Decomposition Results

The system characteristics used for the example and the results we report below are identical to those in the companion paper [4], except we add a 1 MW DG resource at bus 8 that operates at a 0.95 lagging power factor. During weekend days it only operates at 500 kVA (half capacity). We decompose changes from moving from the benchmark tariff where all costs associated losses and fixed network assets and activities are averaged over all MWh to loads to the proposed cost-reflective tariff using full nodal pricing and the Amp-mile method for recovering network fixed costs for loads and DG as we did in the companion paper to this [4].

A. Averaging Losses and Network Costs Versus Averaging Losses and Coincident Peak Network Costs

The definitions of these tariffs do not change with distributed generation, thus we refer the reader to the companion paper [4]. Still we note the full average cost tariff is the sum of (1) and (17), and the average loss plus coincident peak tariff is the sum of (1) and (18). We also note the revenues accruing to DG resources are defined by (2).

Let the full average cost tariff and the average loss plus coincident peak charge tariff be referred to as tariffs 1 and 2 respectively in Table I.

DG has the effect of reducing the overall network costs by reducing line losses for load at all busses. However, DG has no effect on the allocation of network fixed costs under these tariff designs, so all the change between the tariffs with and without DG is driven by the reduction in losses. The reduction in network charges under the fully average cost tariff is 18% for all load customer. However, for the coincident peak tariff, DG has a greater percentage effect for residential loads (29%) and a lower percentage effect for the industrial customer at bus 4 (8%) due to the different base of costs as the industrial customer is driving the peak, while residential customer have low loads at the coincident peak. The reason for this has been in explained in [4], but in short charges for load at k will be greater under coincident peak charges if the individual share of load at coincident peak is greater than the share of average load over the year. However, the actual monetary value of losses reduced is the same under both tariffs.

Still, the result we observed in comparing these two tariffs in [4] still holds. The movement to coincident peak charges to recover network fixed costs has a large effect on who pays for those costs versus averaging.

B. Averaging Losses and Amp-mile Network Charges

This tariff scheme introduces locational aspects into network charges. The charge for load at bus k is the sum of (1), (25), (26), and (28).

$$\begin{aligned} ALAM_{dk} &= \frac{\sum_{t=1}^{T} P_{tk}}{\sum_{t=1}^{T}\sum_{k=1}^{n} P_{tk}} \sum_t Loss_t \lambda_t \\ &+ \sum_{l=1}^{L}(AEoUL_{dlk}^{peak} + REoUL_{dlk}^{peak}) \times ACC_l^{peak} \\ &+ \frac{P_k^{peak}}{\sum_{k=1}^{n} P_k^{peak}} RCC^{peak}. \end{aligned} \tag{29}$$

DG pays a charge for its extent of use

$$\sum_{l=1}^{L}(AEoUL_{glk}^{peak} + REoUL_{glk}^{peak}) \times ACC_l^{peak} \tag{30}$$

We note that if (30) is negative, this is a payment to DG for effectively creating network capacity at peak, and it adds costs that must recovered from all load by the same amount. This potential source of revenue is in addition to proceeds from sales in (2).

The difference in charges to load at bus k between this tariff and the previous tariff with average losses and coincident peak charges is (29) less (1) and(18)

$$\begin{aligned} &\sum_{l=1}^{L}(AEoUL_{lk}^{peak} + REoUL_{lk}^{peak}) \times ACC_l^{peak} \\ &- \frac{P_k^{peak}}{\sum_{k=1}^{n} P_k^{peak}} \sum_{l=1}^{L} \frac{I_l^{peak}}{CAP_l} CC_l \end{aligned} \tag{31}$$

Customers with the same load profile but located at different buses will pay accordingly to their impact on network use. Intuitively, those located far from the PSP will pay more than those located near the PSP. Again, for the ease of presentation, let the tariffs defined by the sum of (1) and(18) and (29) be Tariffs 2 and 3 respectively. The comparison between these two tariffs can be seen in Table II.

TABLE I

EXPENDITURES UNDER DIFFERENT TARIFF SCHEMES WITH AND WITHOUT DG IN USD/YR - 2 VS. 1

Tariff	3	4	5	6	7	8	8-DG
Network cost							
2-NoDG	20400	118547	20400	20400	20400	20400	n/a
2-DG	14543	108688	14543	14543	14543	14543	0
2-DG/NoDG	0.71	0.92	0.71	0.71	0.71	0.71	n/a
1-NoDG	33000	55545	33000	33000	33000	33000	n/a
1-DG	27143	45686	27143	27143	27143	27143	0
1-DG/NoDG	0.82	0.82	0.82	0.82	0.82	0.82	n/a
2/1 NoDG	0.62	2.13	0.62	0.62	0.62	0.62	n/a
2/1 DG	0.54	2.38	0.54	0.54	0.54	0.54	0/0
Total Expenditures							
2-NoDG	257860	522517	257860	257860	257860	257860	n/a
2-DG	252003	512658	252003	252003	252003	252003	-428590
2-DG/NoDG	0.98	0.98	0.98	0.98	0.98	0.98	n/a
1-NoDG	270460	459515	270460	270460	270460	270460	n/a
1-DG	264603	449656	264603	264603	264603	264603	-428590
1-DG/NoDG	0.98	0.98	0.98	0.98	0.98	0.98	n/a
2/1 NoDG	0.95	1.14	0.95	0.95	0.95	0.95	n/a
2/1DG	0.95	1.14	0.95	0.95	0.95	0.95	1.00

TABLE II

EXPENDITURES UNDER DIFFERENT TARIFF SCHEMES WITH AND WITHOUT DG IN USD/YR - 3 VS. 2

Tariff	3	4	5	6	7	8	8-DG
Network cost							
3-NoDG	18356	117901	20569	20675	21064	21984	n/a
3-DG	13012	113714	15133	15196	14862	13955	-4473
3-DG/NoDG	0.71	0.96	0.74	0.73	0.71	0.63	n/a
2-NoDG	20400	118547	20400	20400	20400	20400	n/a
2-DG	14543	108688	14543	14543	14543	14543	0
2-DG/NoDG	0.71	0.92	0.71	0.71	0.71	0.71	n/a
3/2 NoDG	0.90	0.99	1.01	1.01	1.03	1.08	n/a
3/2 DG	0.89	1.05	1.04	1.04	1.02	0.96	-4473/0
Total Expenditures							
3-NoDG	255816	521871	258029	258135	258524	259444	n/a
3-DG	250472	517684	252593	252656	252322	251415	-433063
3-DG/NoDG	0.98	0.99	0.98	0.98	0.98	0.97	n/a
2-NoDG	257860	522517	257860	257860	257860	257860	n/a
2-DG	252003	512658	252003	252003	252003	252003	-428590
2-DG/NoDG	0.98	0.98	0.98	0.98	0.98	0.98	n/a
3/2 NoDG	0.99	1.00	1.00	1.00	1.00	1.01	n/a
3/2 DG	0.99	1.01	1.00	1.00	1.00	1.00	1.01

TABLE III

EXPENDITURES UNDER DIFFERENT TARIFF SCHEMES IN USD/YR - 4 VS. 3

Network cost

Tariff	3	4	5	6	7	8	8-DG
4-NoDG	8883	128348	19589	19961	21017	22752	n/a
4-DG	8521	126139	16326	16511	16324	15022	-17445
4-DG/NoDG	0.96	0.98	0.83	0.83	0.78	0.66	n/a
3-NoDG	18356	117901	20569	20675	21064	21984	n/a
3-DG	13012	113714	15133	15196	14862	13955	-4473
3-DG/NoDG	0.71	0.96	0.74	0.73	0.71	0.63	n/a
4/3 NoDG	0.48	1.09	0.95	0.97	1.00	1.03	n/a
4/3 DG	0.65	1.11	1.08	1.09	1.10	1.08	3.90
Total Expenditures							
4-NoDG	246343	532318	257049	257421	258477	260212	n/a
4-DG	245981	530109	253786	253971	253784	252482	-446035
4-DG/NoDG	1.00	1.00	0.99	0.99	0.98	0.97	n/a
3-NoDG	255816	521871	258029	258135	258524	259444	n/a
3-DG	250472	517684	252593	252656	252322	251415	-433063
3-DG/NoDG	0.98	0.99	0.98	0.98	0.98	0.97	n/a
4/3 NoDG	0.96	1.02	1.00	1.00	1.00	1.00	n/a
4/3 DG	0.98	1.02	1.00	1.01	1.01	1.00	1.03

TABLE IV

EXPENDITURES UNDER DIFFERENT TARIFF SCHEMES IN USD/YR - PROPOSED VS. 4

Network cost

Tariff	3	4	5	6	7	8	8-DG
Prop.-NoDG	8724	93600	27815	28421	29976	31980	n/a
Prop.-DG	8996	113329	22454	22762	22871	21474	-30506
Prop.-DG/NoDG	1.03	1.21	0.81	0.80	0.76	0.67	n/a
4-NoDG	8883	128348	19589	19961	21017	22752	n/a
4-DG	8521	126139	16326	16511	16324	15022	-17445
4-DG/NoDG	0.96	0.98	0.83	0.83	0.78	0.66	n/a
Prop./4-NoDG	0.98	0.73	1.42	1.42	1.43	1.41	n/a
Prop./4-DG	1.06	0.90	1.38	1.38	1.40	1.43	1.75
Total Expenditures							
Prop.-NoDG	246184	497570	265275	265881	267436	269440	n/a
Prop.-DG	246456	517299	259914	260222	260331	258934	-459096
Prop.-DG/NoDG	1.00	1.04	0.98	0.98	0.97	0.96	na
4-NoDG	246343	532318	257049	257421	258477	260212	n/a
4-DG	245981	530109	253786	253971	253784	252482	-446035
4-DG/NoDG	1.00	1.00	0.99	0.99	0.98	0.97	n/a
Prop./4-NoDG	1.00	0.93	1.03	1.03	1.03	1.04	n/a
Prop./4-DG	1.00	0.98	1.02	1.02	1.03	1.03	1.03

TABLE V

EXPENDITURES UNDER DIFFERENT TARIFF SCHEMES IN USD/YR - PROPOSED VS. 1

Network cost

Tariff	3	4	5	6	7	8	8-DG
Prop.-NoDG	8724	93600	27815	28421	29976	31980	n/a
Prop.-DG	8996	113329	22454	22762	22871	21474	-30506
Prop.-DG/NoDG	1.03	1.21	0.81	0.80	0.76	0.67	n/a
1-NoDG	33000	55545	33000	33000	33000	33000	n/a
1-DG	27143	45686	27143	27143	27143	27143	0
1-DG/NoDG	0.82	0.82	0.82	0.82	0.82	0.82	n/a
Prop./1-NoDG	0.26	1.69	0.84	0.86	0.91	0.97	n/a
Prop./1-DG	0.33	2.48	0.83	0.84	0.84	0.79	-30506/0
Total Expenditures							
Prop.-NoDG	246184	497570	265275	265881	267436	269440	n/a
Prop.-DG	246456	517299	259914	260222	260331	258934	-459096
Prop.-DG/NoDG	1.00	1.04	0.98	0.98	0.97	0.96	na
1-NoDG	270460	459515	270460	270460	270460	270460	n/a
1-DG	264603	449656	264603	264603	264603	264603	-428590
1-DG/NoDG	0.98	0.98	0.98	0.98	0.98	0.98	n/a
Prop./1-NoDG	0.91	1.08	0.98	0.98	0.99	1.00	n/a
Prop./1-DG	0.93	1.15	0.98	0.98	0.98	0.98	1.07

An examination of Table II shows the reduction of losses by DG more than offsets that additional network fixed cost that is borne by the load busses. This can be seen as lower tariff charges for the Amp-mile tariff with DG than without DG. As before the changes in charges moving to a locational allocation for network fixed costs is quite small compared to the changes observed in moving to coincident peak charges, though the changes are slightly larger than they were without DG. Still, looking at the percentage of overall energy expenditure, the change in moving toward some locational prices to recover network fixed costs is negligible. As before, the changes in charges in moving from averaging network costs to Amp-mile are really driven by the coincident peak component rather than the locational component, in this example, as the circuits are not fully loaded. If the circuits were close to fully loaded, we might observe more of an effect from the locational charges.

Still, an interesting pattern emerges in the changes in network costs when moving to the a locational signal. The loads closes to the PSP or to the DG resource see a slight decrease while those loads between the generation sources see slight increases in their network charges.

C. Reconciliated Marginal Losses and Amp-mile Network Charges

This tariff charge is the sum of (25), (26), (28), and (13).

$$RLAM_k = \sum_{t=1}^{T} \lambda_t RF_t (\frac{\partial Loss_t}{\partial P_{dtk}} P_{dtk} + \frac{\partial Loss_t}{\partial Q_{dtk}} Q_{dtk})$$
$$+ \sum_{l=1}^{L} (AEoUL_{dlk}^{peak} + REoUL_{dlk}^{peak}) \times ACC_l^{peak}$$
$$+ \frac{P_{dk}^{peak}}{\sum_{k=1}^{n} P_{dk}^{peak}} RCC^{peak}. \quad (32)$$

The revenues for distributed resources under this tariff scheme are given by (14) plus (30).

The difference between this tariff and the previous tariff is (32) less (29) and shows the change in tariff charges due to the movement to pricing losses at the margin, introducing time-of-use and locational considerations into this aspect of the distribution tariff while keeping the amp-mile methodology for recovery of network fixed costs.

$$\sum_{t=1}^{T} \lambda_t RF_t (\frac{\partial Loss_t}{\partial P_{dtk}} P_{dtk} + \frac{\partial Loss_t}{\partial Q_{dtk}} Q_{dtk})$$
$$- \frac{\sum_{t=1}^{T} P_{dtk}}{\sum_{t=1}^{T} \sum_{k=1}^{n} P_{dtk}} \sum_{t} Loss_t \lambda_t \quad (33)$$

Let the tariffs in equation (29) and (32) be Tariffs 3 and 4 respectively. The comparison between these two tariffs can be seen in Table III. The presence of DG alters the incremental change from the average loss tariff to the reconciliated marginal loss tariff as can be seen in Table III. Instead of some busses seeing a decrease in network charges, as was the case without DG, all busses except for bus 3 realize increases in network charges between 8% and 11%. This changes reflects the idea that DG, under average losses, was not compensated at marginal cost for its contribution to loss reduction, which it is now at "reconciliated marginal cost" prices. Without DG, the effect of moving to reconciliated marginal losses was simply a reallocation of the cost of losses by location. In the presence of DG, the effect of moving to reconciliated marginal losses also picks up the idea that losses are essentially "subsidized" under averaging.

However, much like the case without DG, the change in charges with respect to total energy expenditures is quite small on the order +/- 2% in moving from average losses to reconciliated marginal losses.

D. Full Marginal Losses and Amp-mile Network Charges

This is the sum of (25), (26), (28), and (5)

$$MLAM_k = \sum_{t=1}^{T} \lambda_t (\frac{\partial Loss_t}{\partial P_{dtk}} P_{dtk} + \frac{\partial Loss_t}{\partial Q_{dtk}} Q_{dtk})$$
$$+ \sum_{l=1}^{L} (AEoUL_{dlk}^{peak} + REoUL_{dlk}^{peak}) \times ACC_l^{peak}$$
$$+ \frac{P_{dk}^{peak}}{\sum_{k=1}^{n} P_{dk}^{peak}} RCC^{peak}. \quad (34)$$

The revenues for distributed resources under this tariff scheme are given by (6) plus (30).

The difference between this tariff and the previous tariff is (34) less (32) less the merchandising surplus subtracted from the network fixed cost for the purposes of computing the amp-mile tariff.

$$\sum_{t=1}^{T} \lambda_t (1 - RF_t)(\frac{\partial Loss_t}{\partial P_{dtk}} P_{dtk} + \frac{\partial Loss_t}{\partial Q_{dtk}} Q_{dtk})$$
$$- \sum_{l=1}^{L} (AEoUL_{dlk}^{peak} + REoUL_{dlk}^{peak}) \frac{I_l^{peak}}{CAP_l} MS$$
$$- \sum_{l=1}^{L} MS(1 - \frac{I_l^{peak}}{CAP_l}) \frac{P_{dk}^{peak}}{\sum_{k=1}^{n} P_{dk}^{peak}} \quad (35)$$

where MS is the merchandising surplus defined in equation (8).

The results for this comparison can be seen in Table IV. Much like the case without DG, bus 4 realizes a decrease in distribution charges moving to full marginal losses. However, the decrease is not nearly as great in percentage terms and the final tariff charge is much greater than without DG. The presence of DG reduces losses and hence reduces the merchandising surplus under full nodal pricing so the amount of rebate the industrial customer can receive is less. Add into this DG is paid for creating capacity, so there are more costs to recover. Bus 3, closest to the PSP, sees a small increase in its charges moving to full nodal pricing for losses for similar reasons as bus 4. For the remaining busses on the system, the increase in network charges is not much different than the case without DG, in the range of 38% to 43% increases for network charges driven by their contribution to marginal losses because of distance and the idea that they do not contribute much to the coincident peak and would thus receive little back in the way of a rebate from the merchandising surplus.

E. Benchmark Average Cost Tariff vs. Proposed Cost Reflective Tariff

Having looked at the decomposition of the tariff changes, we examine the complete change in moving from the average cost tariff to the proposed cost reflective tariff in Table V. We observe that residential loads far from PSP see a decrease in distribution tariff charges moving toward the nodal pricing, amp-mile method in the presence of DG which again is counterintuitive in that one would have expected these loads to see tariff charges increase. More intuitively, however, the presence of DG led to greater decreases for these loads as it reduced marginal losses for busses 5-8. Bus 3 still observes a decrease, but not as great in percentage terms as without DG.

Bus 4, the industrial customer, realizes an enormous 148% increase in network charges. There are three main drivers for this result. First, as was the case without DG, the industrial customer is driving the coincident peak and bears the greatest share of network fixed costs. Second, the presence of DG reduces the merchandising surplus available to rebate back to this customer through reductions in the network fixed costs that are allocated. Third, and minor compared to the first two effects, is the fact that DG is being paid for effectively creating capacity and for reducing losses at nodal prices and this adds to the network costs that must be recovered.

Overall, in the context of total expenditures, busses 5-8 realize a 2% decrease in charges, bus 3 realizes a 7% decrease, and bus 4 a 15% increase. With the exception of bus 4, the percentage changes are quite similar to the case without DG. In absolute monetary terms, busses 5-8 realize reduced charges with DG, while bus 3 sees a slight increase and bus 4 sees a 21% increase. Consequently, not everybody on the network benefits from DG in our proposed tariff, and the benefits accrue to busses closest to DG. However, DG revenues increase in the transition by 7% in total, with 3% gains being attributable to movements to reconciliated nodal pricies and full nodal prices respectively and 1% to moving to the amp-mile tariff.

V. Conclusion

In this paper we have shown a decomposition of the changes in distribution tariff charges in moving from a purely average cost tariff structure to a more cost-reflective tariff structure with full marginal losses and an extent-of-use (Amp-mile) method for the recovery of network fixed costs in the presence of distributed generation. Much like the case without DG, the movement to coincident peak charges and to full marginal losses have the largest effects. However, DG adds nuances to analyzed effects. With respect to moving to reconciliated marginal losses, DG exposes the idea that paying for losses at higher prices shows how load is being “subsidized” under loss averaging. Moreover, DG increase the network fixed costs that must be recovered as if effectively creates network capacity, DG reduces line losses overall and thus reduces the merchandising surplus that can be rebated back to load by offsetting network fixed cost. Finally, DG, while benefiting those closest to it, seems to increase network charges to other loads on the network. It is important to note in the final analysis that the effects of tariff changes in the presence of DG may change considerably with different load profiles and different topologies.

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J. Mario Vignolo (M’1997) was born in Montevideo, Uruguay, in 1972. He graduated from the School of Engineering, UDELAR, Montevideo in 1998. He received an MSc. degree in Electrical Power Engineering from UMIST, Manchester, U.K. in 2001. At the moment he is an Assistant Professor at the School of Engineering in Montevideo.

Dr. Paul Sotkiewicz has been the Director of Energy Studies at the Public Utility Research Center (PURC), University of Florida since 2000. Prior to joining PURC, Dr. Sotkiewicz was a staff economist at the United States Federal Energy Regulatory Commission (FERC) working on market design issues related to the New York ISO and the California ISO. He received his BA in economics and history from the University of Florida in 1991, and his M.A. (1995) and Ph.D. (2003) in economics from the University of Minnesota.