An *Ex-post* Energy Rate Mechanism for Distribution Networks based on Real Time Metering

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***Abstract*—The integration of generation units into distribution networks has led to a definition for the rates associated with the injections of power, as traditional distribution networks only consider tariffs for energy consumption. Such rate definitions have considered several aspects of the problem (such as the cost of operating the distribution network, the nature of the injections and feed-in tariff), so rates amongst different systems differ, not only because of the different energy prices but also because of different definitions that may not be consistent. This paper proposes a systematic definition for the injection tariff in distribution systems. The definition considers that the distribution system has a given operation cost, and that the tariff must be dynamic to represent the contribution of the injection (negative or positive) to the cost of operating the distribution system.**

***Index Terms*—Net metering; Feed in tariff**

I. INTRODUCTION

The integration of distributed generation has been identified as a necessary change in the paradigm of distribution system operation, and significant efforts have been deployed to develop the concept. Those efforts rely on the various benefits of Distributed Generation (DG), widely described in the literature. Thus, the large scale integration of distributed generation is expected to be a reality in the short term.

The integration of DG has posed technical difficulties, mainly in terms of smart grid-based distribution protection schemes, smart grid data privacy, and retail companies revenue shortfall. In general, Smart Grid infrastructure has been widely treated in the literature [1]. The protection schemes for dynamic operation of DG have been developed [2], [3], [4], with successful implementations the industry [5]. Data privacy has been a significant concern in the US, leading to important efforts from the government to ensure data privacy in smart grid data [6]. A third concern is related to the financial operation of retail companies, and the reduction in the energy revenues of such companies in the presence of DG. The integration of DG strongly depends on the rate for DG power injections that should represent:

- the cost of operating the distribution grid, and
- the value of the DG injection, which must consider the positive and negative impacts of the injection on the distribution system.

These points define the cost effectiveness of DG technologies towards the massive integration expected from the authority, so it is a central problem in terms of the long term sustainability of DG.

The problem of DG injection rates have been discussed in several works. In [7], the application of net metering in different systems is discussed. Although no particular rate system is proposed, it is noted that there is a need for coordination and dynamic pricing. In [8], the incentive for energy storage in the presence of net metering and variable injection rates is discussed. It is shown that time-of-use rates may be of interest for storage use, but a discussion on the price mechanism and its impact is not presented. In [9] and [10], the current DG injection rate mechanisms are described. It is noted that rate mechanisms are not well developed in general. In [11], the benefits of time-of-use retail prices are discussed. In one hand, the use of PV is incentivized as time-of-use prices intend to be high during peak hours, which is correlated with sun power peaks. On the other hand, it is shown that time-of-use prices reduce overall energy costs as peaks are reduced, committing less units to satisfy electric demand in the wholesale market. However, the remuneration of retail companies as DG increases is not discussed. In [12] the impact of net billing pricing is discussed in the context of Chile. Retail company remunerations are described as a significant problem to net metering, so a lower rate for DG injection (net billing) is considered. The results show a low economic incentive for DG integration. Time-of-use or other rate mechanisms are not described. In [13] and [14], the impact of flat, time of use, and real time pricing on PV integration in the U.S. is presented. The study shows that different rate systems affect the level of PV penetration, being time of use the most significant in increasing PV penetration. None of the studies investigate the reduction in retailer operational margins or the fixed cost of the distribution grid operation.

The concerns of net metering are expressed in [15] and [16]. They mainly rely on the lack of analysis of the cost of net metering in terms of reduction in distribution profit, which affects the price of electricity to costumers as well as the revenue of retailers that face a reduction in gross sales.

This paper proposes a new method for pricing GD injections in distribution systems. The method considers an *ex-post* rate mechanism that represents the value of injecting and consuming and the cost of operating the distribution system.

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An example will be presented to show numerical results.

II. RATE FOR INJECTIONS IN DIFFERENT SYSTEMS

One of the aspects that shows an open discussion on DG injection rates is the variety of mechanisms depending on the system. This section presents a brief review of such mechanisms in different systems. The following definitions will be used throughout:
Net metering: the DG injection is considered as a negative consumption, so it is valued at the same rate consumption is.
Net billing: the DG injection has a different value (normally lesser) than that of consumption rate.
Feed-in tariff: the DG injection receives a payment depending on the nature of the resource (generally renewable), which is not necessarily connected to the retail price.

A. Australia, met metering

Australia has both net metering and feed-in tariff in case the DG unit is renewable (specially solar), and several Australian states have enacted the initiative; the subsidy has been fostered in response to the Australian renewable energy targets. Thus, solar DG injections are subject to net metering and receive a monthly payment, which has produced an increment in solar PV from 50 MW to 4 GW in 5 years. However, concerns have arisen in term of retailer's revenue from gross energy reduction [17], [18].

B. Germany, feed-in tariff

Germany has a feed-in tariff mechanism to rate power injections from renewable DG. The feed-in tariffs are differentiated by technology: 0.044 US$/KWh for hydro up to 50 MW, 0.128 US$/KWh for rooftop PV up to 30 kW, and 0.2550.173 US$/KWh for offshore wind (residential electricity price in Germany is about 0.35 US$/KWh). The feed-in tariffs have been decreased to better represent market prices, and several concerns have arisen in terms of what is the right price for DG injections and how these partial definitions are problematic [19] [20].

C. Chile, net billing

Chile has a net billing mechanism. The mechanism consist of paying to DG injections (less than 100kW) a rate equivalent to that paid by the distribution company in the electricity market and the saving from less losses in the distribution system [12]. That rate may $\frac{1}{3}$ of the distribution electricity rate, depending on the location of the DG. This rate mechanisms does not represent the contributions of the DG injection, such as peak shaving and system marginal costs reduction.

III. ANALYSIS ASSUMPTIONS

The proposed method considers the following assumption in term of distribution operation:

1) the distribution system has only one retailer,
2) real time metering based on smart grid is available, and
3) real time prices from the wholesale market are represented to some extend into the retail price.

Assumption 1 considers, for simplicity, that there is only one retailer that operates at marginal cost. This represents, without loss of generality, the behavior of many retail agents operating in an non-concentrated market.

Assumption 2 assumes that all costumer meters have communication to the distributor operator or have data logger capability to store daily power profiles. This information will be used to determine the tariffs.

Assumption 3 implies that the retailer aggregates wholesale variable prices to obtain the cost of satisfying the retail demand. This aggregation is performed in several manners depending on the country, varying from long term bilateral contracts between the retailer and the generator, to close to real time exposure of the retail costumers to real time electricity prices. In any case, assumption 3 states that wholesale market prices have a direct relationship with, and drives retail costs so if wholesale market prices decrease, retail prices do as well.

Within the assumptions of this work, the method intends to capture several aspects of DG integration:

- ensure that the cost of grid operation is shared amongst all users,
- represent a systematic rate for DG injections, considering the impact on system energy marginal costs (peak shaving, congestion), and
- establish a consistent incentive on DG to operate in a particular time of the day where the impact on the whole sale market or the distribution operation causes a reduction in total costs.

IV. PROPOSED METHOD

On one hand, the proposed methods separates the fixed costs of operation the distribution system from those associated with energy sales. The idea is to define different administrative and financial entities in charge of the operation and energy sales (retailer), so the fixed cost of operating the system is ensured by the rate mechanism. If DG generation increases, the retailer has to adapt to the new net demand through a regular market process. DG and the retailer are, in this scenario, market participants of the retail market; the proposed rule will ensure that the retailer will get paid for the total energy that is sold at the *ex-ante* price of the retailer. However, the amount of energy sold will depend on the amount of DG during the operating period. Thus, the problem of remunerating the distribution operation is solved.

On the other hand, the idea of the price mechanism is to incentivize the demand curve to be flat. This is consistent with the fact that load peaks lead to both more expensive generation needed to satisfy demand and transmission congestion. Thus, a flat load profile is desirable.

The load profile can be insentivized to be flat in several manners. If the load profile presents a peak, it is desirable that DG units inject energy, and that loads decrease consumption. On the contrary, if the load profile presents a valley, the incentive should be to consume energy and reduce DG. This behavior can be induced by a price mechanism.

Let C_D (\$) be the daily operational cost associated with the physical distribution system functioning, C_R (\$) the cost of one day of operation of the retailer, and let C_E (\$) be the cost of the energy consumption, which will be associated with the cost of the energy purchased in the market by the retailer to satisfy the demand. This energy cost may come from a bilateral contract, an auction, or a purchase in the wholesale/real time market that the retailer performs. C_D and C_R are, in general, fixed costs, while C_E depends on the energy consumption in one day Q_E (kWh) and the price of the energy given by the retailer, p_E (\$/kWh), which is the price the retailer pays for the energy. Such a price p_E will be assumed to be constant during the day, and representative of the wholesale average price during that day. The formulation will assume that daily operation costs at the end of the day will be known, so with such an information an *ex-post* can be formulated.

Let $\mathcal{K}$ be the set of equal periods of the day, and $k \in \mathcal{K}$ a particular period. Let $\mathcal{I}$ be the set of distribution "prosumers" (can be either a consumer of producer of energy) within the distribution company, and $d_{i,k},\ i \in \mathcal{I}, k \in \mathcal{K}$ the net power demand of prosumer i in period k respectively. Let p_k^+ (\$/kWh) and p_k^- (\$/kWh) the price of injection and withdrawal of energy within the distribution system at period k. Both p_k^{inj} and p_k^{wth} will represent the *ex-post* prices after a day of operation. The following relationship must be true in the context of the rate mechanism:

$$\sum_{k\in\mathcal{K}} \Delta T \left(P_k^- p_k^- - P_k^+ p_k^+\right) = C_D + C_R + C_E, \qquad (1)$$

where p_k^{inj} and p_k^{wth} are to be determined, ΔT (hours) is the length of each interval, and P_k^- (kW) and P_k^+ (kW) are the net power withdrawal and injections at period k defined as follows:

$$P_k^+ = \sum_{i\in\mathcal{I}} -\min(d_{i,k}, 0), \quad k \in \mathcal{K} \qquad (2)$$

$$P_k^- = \sum_{i\in\mathcal{I}} \max(d_{i,k}, 0), \quad k \in \mathcal{K}. \qquad (3)$$

Proposition: Let $P_k = P_k^- - P_k^+$ be the net power demand of the distribution system, and let $\overline{P_k}$ the average value of P_k. Let N be the number of pricing intervals. The following tariff rule:

$$P_k^- p_k^- - P_k^+ p_k^+ = P_k p_E + P_k \frac{C_D + C_R}{\overline{P_k} N \Delta T} \qquad (4)$$

$$p_k^- - p_k^+ = \alpha p_E * \frac{\overline{P_k} - P_k}{\overline{P_k}} \qquad (5)$$

$$P_k^- \neq P_k^+ \qquad (6)$$

1) satisfy remuneration to distribution operation and retailing (1),
2) establish flat rates for withdrawals if total injections are null,
3) satisfy net metering when net demand equals average demand (peak shaving), and
4) insentivize distribution participants to flatten total retailing demand.

Proof:

1) Multiplying (4) by ΔT in both sizes an summing over $k \in \mathcal{K}$:

$$\begin{aligned}
\Delta T \sum_{k\in\mathcal{K}} (P_k^- p_k^- - P_k^+ p_k^+) &= \\
&= \Delta T \sum_{k\in\mathcal{K}} \left(P_k p_E + P_k \frac{C_D + C_R}{\overline{P_k} N \Delta T} \right) \\
&= p_E \sum_{k\in\mathcal{K}} P_k \Delta T \frac{C_D + C_R}{\overline{P_k} \Delta T} + \frac{1}{N} \sum_{k\in\mathcal{K}} P_k \\
&= p_E Q_E + \frac{C_D + C_R}{\overline{P_k}} \overline{P_k} \qquad (7) \\
&= C_E + C_D + C_R \blacksquare \qquad (8)
\end{aligned}$$

2) From (5), if $\overline{P_k} = P_k$, then $p_k^- = p_k^+$, which satisfies net metering $\blacksquare$

3) From (4) $P_k^- p_k^- = P_k p_E + P_k \frac{C_D + C_R}{\overline{P_k} N \Delta T}$ when $P_k^+ = 0$. Also, $P_k^- = P_k$ if $P_k^+ = 0$. Thus,

$$\begin{aligned}
p_k^- &= \frac{P_k^- p_E + P_k^- \frac{C_D + C_R}{\overline{P_k} N \Delta T}}{P_k^-} \\
&= p_E + \frac{C_D + C_R}{\overline{P_k} N \Delta T} \blacksquare \qquad (9)
\end{aligned}$$

4) Note from (5) that if net demand is above average demand $\overline{P_k} < P_k$, then $p_k^- < p_k^+$, insentivizing injection and leading to a reduction in peak demand. If net demand is below average demand $\overline{P_k} > P_k$, then $p_k^- > p_k^+$ insentivizing withdrawal and leading to a increment in net demand. This insentivizes consumption during low load periods and injection during high demand periods $\blacksquare$

The formulation includes a factor α that is intended to modulate the effect of price differentiation and how strong the incentives to consume or inject are.

The tariff rule (4)(5)(6) consist of a linear system

$$\begin{bmatrix} P_k^- & -P_k^+ \\ 1 & -1 \end{bmatrix} \begin{bmatrix} p_k^- \\ p_k^- \end{bmatrix} = \begin{bmatrix} P_k p_E + P_k \frac{C_D + C_R}{\overline{P_k} N \Delta T} \\ \alpha p_E * \frac{\overline{P_k} - P_k}{\overline{P_k}} \end{bmatrix} \qquad (10)$$

that may be infeasible. The rule is infeasible when $P_k^- = P_k^+$ (singular matrix). This condition implies that the total energy needed within the distribution system is provided by distributed generation, so there is no price definition from outside the distribution system. Another rule is needed in such a case, which is left for future work.

TABLE I
SYSTEM DEMAND

Period	1	2	3	4	5	6	7
P_k^- (kW)	110	150	180	190	185	140	110

V. EXAMPLE

A seven-period example is presented with periods of one hour. The demand of the system is shown in Table I.

For all the examples, $C_D + C_R = \$25000$, p_E = 50, ΔT = 1, and α = 1.

A series of iterations will be considered, assuming that total daily demand stays constant, and that variable generation can dispatched if convenient. The first example is a scenario with no distributed generation shown in Table II.

TABLE II
SCENARIO 1

Period	1	2	3	4	5	6	7
P_k	110	150	180	190	185	140	110
P_k^+	0	0	0	0	0	0	0
P_k^-	110	150	180	190	185	140	110
p_k^-	73	73	73	73	73	73	73
p_k^+	60	73	83	86	84	69	60
$P_k^- p_k^-$	8082	11021	13225	13960	13593	10286	8082
$P_k^+ p_k^+$	0	0	0	0	0	0	0

In this case, total payment to the distribution system is \$ 78,250, which is exactly the cost of running the system.

It can be seen that from table II that in period 3, 4 and 5 the price for injection is larger than the price for withdrawal, so it is an incentive for DG production at those times. In table III, a new condition is shown. For periods 3,4 and 5, 60 kWh are generated.

TABLE III
SCENARIO 2

Period	1	2	3	4	5	6	7
P_k	110	150	120	130	125	140	110
P_k^+	0	0	**60**	**60**	**60**	0	0
P_k^-	110	150	180	190	185	140	110
p_k^-	78	78	77	79	78	78	78
p_k^+	72	88	74	80	77	84	72
$P_k^- p_k^-$	8607	11737	13856	14991	14426	10955	8607
$P_k^+ p_k^+$	0	0	4466	4819	4645	0	0

Now, power production is convenient in period 2 and 6, and 30 kWh are placed in those periods. The results are shown in Table IV.

It is clear that the signal prices move the net demand curve to be flatter, as shown in Fig. 1.

The effect of α can be seen in Table VI, where α is set to 5 for the same condition of scenario 3:

The effect of the factor α is to increase the sensitivity of the price signal with respect to the action tending to the flatten the net demand curve. For example, scenario 5 shows the same condition of scenario 4 but for α = 0.1.

TABLE IV
SCENARIO 3

Period	1	2	3	4	5	6	7
P_k	110	120	120	130	125	110	110
P_k^+	0	**30**	60	60	60	**30**	0
P_k^-	110	150	180	190	185	140	110
p_k^-	80	81	81	83	82	79	80
p_k^+	77	81	82	88	85	76	77
$P_k^- p_k^-$	8833	12080	14536	15709	15125	11115	8833
$P_k^+ p_k^+$	0	2443	4900	5270	5087	2282	0

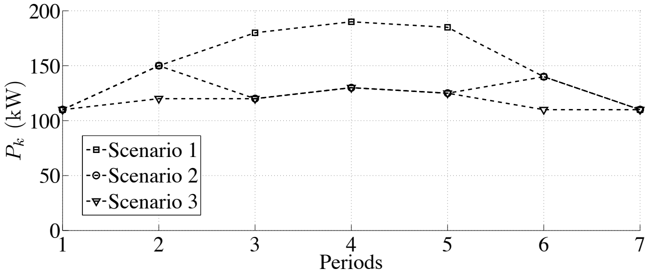

Fig. 1. Net demand power profile

For α = 0.1, P_k^+ and P_k^- are very close to each other, showing less senility to to the action tending to flatten the net demand curve.

VI. CONCLUSIONS AND FUTURE WORK

This work proposes a rate mechanism for DG injections that is consistent with economic principles. The hypothesis of the mechanism is that distribution net demand should be flat to minimize peak (expensive) generation and to minimize transmission congestion. The pricing rule was shown to determine prices consistent with incentives to flatten net demand curves by the integration of distributed generation. Also, the pricing rule separates the fixed costs of the distribution system from the energy costs, so the cost of operating the distribution system are guaranteed and the profit from energy sales are only associated to a retailer. Note that the retailer has to compete with distributed generator, so separation of distribution operation from retailing is necessary for this rate mechanism to work. In the long term, the reduction of wholesale prices will impact on p_E, decreasing the total cost of operation, which is the desired effect, and the actual usefulness of DG in the context of retail markets.

Several aspects are listed as future work.

- The proposed formulation is consistent with several aspects of interest, but its general validity in a broader context was not shown. In particular, the convergence of the formulation needs to be shown in a general context for any pofit-maximizing bidding policy. For example an agent of game theory approach may be suitable for the analysis, but also deterministic policies are of interest.
- The sensitivity of the pricing rule with respect of some parameters was not explored. For example, the sensitivity of the pricing rule with respect to p_E, the external price

TABLE V
SCENARIO 4

Period	1	2	3	4	5	6	7
P_k	110	120	120	130	125	110	110
P_k^+	0	30	60	60	60	30	0
P_k^-	110	150	180	190	185	140	110
p_k^-	**80**	**81**	**83**	**92**	**88**	**76**	**80**
p_k^+	**64**	**86**	**87**	**118**	**103**	**59**	**64**
$P_k^- p_k^-$	8833	12216	14864	17516	16202	10606	8833
$P_k^+ p_k^+$	0	2580	5227	7077	6164	1773	0

TABLE VI
SCENARIO 4

Period	1	2	3	4	5	6	7
P_k	110	120	120	130	125	110	110
P_k^+	0	30	60	60	60	30	0
P_k^-	110	150	180	190	185	140	110
p_k^-	80	80	80	81	80	80	80
p_k^+	80	80	80	81	81	80	80
$P_k^- p_k^-$	8833	12049	14463	15303	14883	11230	8833
$P_k^+ p_k^+$	0	2413	4826	4863	4845	2396	0

for energy the retailer sets. Also, in a scenario with exposure to wholesale real time prices, p_E can be a variable or a forecasting stochastic process.

- The influence of a marginal cost for distributed generator was not explored. It is clear that distributed generation units may have a marginal cost of operation, so distributed generation units will respond by increasing production if the price is consistent with its marginal costs. In the context of this work, generation was assumed to be incentived if the price of injection was higher than the withdrawal price, so a different response can be obtained in that scenario.
- The trend of the parameter α was explored through simulations, but no specific criteria for its value was considered. The value may be associated with the regulatory effect the specific authority want to impose, but an optimal setting is proposed for a future work.
- In general, distributed generator recourses are not dispatchable (such as solar power) so the analysis may consider this aspect in a future work. The analysis should consider the correlation between solar radiation and net demand to determine, for example, the expected level of solar power penetration in the presence of the proposed tariff rule.
- Future work is proposed to analyse the impact of this rate mechanism on storage of devices, such as batteries. Considering the marginal cost of operation of batteries and the elasticity of electricity demand, conclusions on the optimal economic amount of storage capacity can be drawn.
- Another point left for future work is the impact of p_E reduction on DG integration. In principle, the benefit from p_E reduction should be entirely assumed as a profit for DG, but the proposed method assumes that a reduction in p_E will also lead to a reduction in the DG profit. A discussion on whether the benefits from peak shaving should be entirely or partially included in DG profit is proposed as a future work.

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