Nodal Pricing for Distribution Networks: Efficient Pricing for Efficiency Enhancing DG

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***Abstract*—As distributed generation (DG) becomes more widely deployed, distribution networks become more active and take on many of the same characteristics as transmission. We propose the use of nodal pricing that is often used in the pricing of short-term operations in transmission. As an economically efficient mechanism, nodal pricing would properly reward DG for reducing line losses through increased revenues at nodal prices and signal prospective DG where it ought to connect with the distribution network. Applying nodal pricing to a model distribution network, we show significant price differences between buses reflecting high marginal losses. Moreover, we show the contribution of a DG resource located at the end of the network to significant reductions in losses and line loading. We also show the DG resource has significantly greater revenue under nodal pricing, reflecting its contribution to reduced line losses and loading.**

***Index Terms*—Distributed generation (DG), distribution networks, loss allocations, nodal pricing.**

I. Introduction

As distributed generation (DG) becomes more widely deployed in distribution networks, distribution takes on many of the same characteristics as transmission in that it becomes more active rather than passive. Consequently, pricing mechanisms that have been employed in transmission, such as nodal pricing as first proposed in [1], are good candidates for use in distribution. Nodal pricing is an economically efficient pricing mechanism for short-term operation of transmission systems that has been implemented in various forms by electricity markets in New York, New England, PJM, New Zealand, Argentina, and Chile. Clearly, this is a pricing mechanism with which there is a great deal of experience and confidence.

While nodal pricing is most often associated with pricing congestion as discussed in [2], the pricing of line losses at the margin, which can be substantial in distribution systems with long lines and lower voltages, can be equally important. In this short paper, we propose using nodal pricing in distribution networks to send the right price signals to locate DG resources and to properly reward DG resources for reducing line losses through increased revenues derived from prices that reflect marginal costs.

II. Nodal Pricing in a Distribution Network

The manner in which we derive nodal prices in a distribution network is no different from deriving them for an entire power system. Let t, k, g, and d be the indexes of time, buses, generators at each bus k, and loads at each bus k. Define P_{kg}, Q_{kg}, P_{kd}, and Q_{kd} respectively, as the active and reactive power injections and withdrawals by generator g or load d located at bus k. The interface between generation and transmission, the power supply point (PSP), is treated as a bus with only a generator. P and Q without subscripts represent the active and reactive power matrices, respectively.

Let $C_{kg}(P_{kg}, Q_{kg})$ be the total cost of producing active and reactive power by generator g at bus k, where C_{k_g} is assumed to be convex, weakly increasing, and once continuously differentiable in both of its arguments. The loss function $\mathrm{Loss}(P, Q)$ is convex, increasing, and once continuously differentiable in all of its arguments. We assume no congestion on the distribution network and that generator prime mover and thermal contraints are not binding.

The optimization problem for dispatching DG and power from the PSP can be represented as the following least-cost dispatch problem at each time t:

$$\min_{\substack{P_{kgt}, Q_{kgt} \\ \forall kg, kd}} \sum_k \sum_g C_{kg}(P_{kgt}, Q_{kgt}) \tag{1}$$

subject to

$$\mathrm{Loss}(P, Q) - \sum_k \sum_g P_{kgt} + \sum_k \sum_d P_{kdt} = 0, \forall t. \tag{2}$$

Application of the Karush–Kuhn–Tucker conditions lead to a system of equations and inequalities that guarantee the global maximum [3].

Define the net withdrawal position for active and reactive power at each bus k at time t by $P_{kt} = \sum_d P_{kdt} - \sum_g P_{kgt}$ and $Q_{kt} = \sum_d Q_{kdt} - \sum_g Q_{kgt}$. Nodal prices are calculated using power flows locating the "reference bus" at the PSP, so λ_t corresponds to the active power price at the PSP. Assuming interior solutions, we obtain the following prices for active and reactive power, respectively:

$$pa_{kt} = \lambda_t \left(1 + \frac{\partial \mathrm{Loss}}{\partial P_{kt}}\right), pr_{kt} = \lambda_t \left(\frac{\partial \mathrm{Loss}}{\partial Q_{kt}}\right). \tag{3}$$

III. DG Revenue: Nodal Pricing versus Price $= \lambda_t$

Suppose as the alternative to nodal pricing that the DG resource would receive the price at the interface with the transmission system at each time period λ_t. Over all time periods during the year, the DG resource would then have revenue equal to

$$R_\lambda = \sum_t \lambda_t P_{kt}. \tag{4}$$

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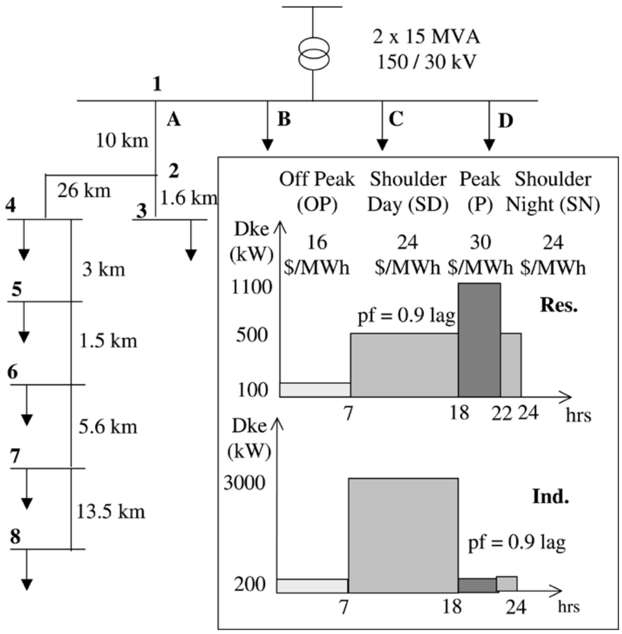

Fig. 1. Rural distribution network with residential and industrial load profiles.

This revenue does not reflect a DG resource's contribution to losses (either positive or negative), as does nodal pricing. The nodal pricing revenue for a DG resource located at bus k over the year is expressed as

$$R_n = \sum_t \left(\lambda_t \left(1 + \frac{\partial \text{Loss}}{\partial P_{kt}} \right) \right) P_{kt} + \lambda_t \left(\frac{\partial \text{Loss}}{\partial Q_{kt}} \right) Q_{kt}. \quad (5)$$

The difference in revenue between receiving the nodal price and simply receiving λ in each time period is $R_n - R_\lambda$ and reflects in aggregate the contribution toward the reduction (increase) in losses. If the DG resource reduces losses, then nodal pricing will yield higher revenue. However, if it increases losses, it will receive less revenue.

IV. Example

We consider a rural radial distribution network, meant to reflect conditions in Uruguay where there are long lines. The network is shown in Fig. 1. The overhead lines in the network are type 120AlAl with $r(\Omega/\text{km}) = 0.3016$ and $x(\Omega/\text{km}) = 0.3831$. Bus (1) is fed by a 150/30-kV transformer and four radial feeders (A, B, C, D), but for simplicity, we will just consider feeder A for our calculations. Feeder A consists of a 30-kV overhead line feeding five residential 30/15-kV buses (3, 5, 6, 7, 8) and an industrial customer at bus 4.

The network configuration as well as the load profiles for industrial and residential customers shown in Fig. 1 are reflective of what might be observed in Uruguay. For each of the four time periods during the day, abstracting from seasonal variations, the prices in US$/MWh at bus 1 (PSP) are given in Fig. 1 as well.

We optimize the network following [4] for two cases: 1) no DG resource; and 2) a 1-MVA DG resource located at bus 8 operating at 0.95 lagging power factor and assuming the DG resource has a cost that is below λ_t in all hours t. Prices at bus 8 at the end of the network with and without DG in all time periods, as well as prices in the peak period for all buses, are shown in Table I. The revenue for DG under nodal pricing and "λ pricing" is shown in Table II.

TABLE I
PRICES AT BUS 8 AND PRICES AT PEAK

Prices at Bus 8

	No DG		DG	
Time	p_a	p_r	p_a	p_r
OP	16.2976	0.1456	15.6928	-0.0512
SD	28.8336	2.6496	27.1704	1.9056
P	36.732	3.702	34.473	2.634
SN	25.9872	1.0176	24.8448	0.5832

Prices at All Busses at Peak

	No DG		DG	
Bus	p_a	p_r	p_a	p_r
1	30	0	30	0
3	31.503	0.9	31.182	0.702
4	35.118	2.901	33.771	2.184
5	35.571	3.129	34.083	2.349
6	35.742	3.216	34.191	2.409
7	36.183	3.432	34.41	2.541
8	36.732	3.702	34.473	2.634

TABLE II
DG REVENUE: NODAL VERSUS λ

R_λ	R_n	% difference
188632	210448	12

V. Discussion and Conclusion

For our model network, we show the DG resource can provide benefits to the network through reduced line losses and line loading by 37% and 18%, respectively, as well as reducing voltage changes by 25%. From Table I, we can see the price impact of losses with and without the DG resource. DG resources should be appropriately rewarded, through nodal pricing, as can be seen by the revenue in Table II, for providing such benefits to the distribution system.

Without the efficient incentives presented by nodal pricing through higher prices leading to larger revenues for DG resources, there is little hope of inducing DG resources to locate and operate so they can provide the system benefits as shown above. Given worldwide experience with nodal pricing, and the fact that DG resources transform the distribution network into an active network-like transmission, it makes sense to consider nodal pricing in distribution.

References

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