DETERMINATION OF MINIMUM GUARANTEED PURCHASING PRICE FROM RENEWABLE SOURCES AT DISTRIBUTION NETWORK BUSES WITH CONSIDERATION INVESTMENT DYNAMICS

Seyyed Majid Miri- Larimi
Tarbiat Modares University of Tehran – Iran
m.miri@modares.ac.ir

Mahmoud-Reza Haghifam
Tarbiat Modares University of Tehran – Iran
haghifam@modares.ac.ir

ABSTRACT

With presence of renewable energy sources (RES) in electric distribution networks, utilities have the options to purchase energy from RES units and/or directly from the wholesale electricity market. The utility's desired purchasing price of RES energy depends on their impacts on network, and as well as wholesale market price. This paper proposes a method to determine the minimum guaranteed purchasing price of RESs energy with consideration their impacts on loss, investment deferral, and air pollution. These prices are as efficient economical signal so that lead the investors to installation of RES at buses with more positive technically impact in distribution network. The investment dynamics is also considered in the proposed method.

INTRODUCTION

Distributed generation (DG) can provide benefits to the distribution utility such as power losses and environmental pollution reduction, investments deferral, and reliability indices improvement [1]. The utility might be willing to buy energy from DGs that are optimally located in the distribution network. To supply the demand of its network, a utility purchases energy from wholesale market. Most of this energy is bought through long-term bilateral contracts at a price based on the wholesale electricity market price. In presence of DGs, the utility has the option to purchase energy from any DG units owned by investor, and directly from the wholesale electricity market. The amount of energy and the price at which purchased by utility are related to the DG's impact on network and the wholesale market price. If DG unit power production has positive technically impact, then the DG energy price is slightly higher than the wholesale market price. Conversely, if the DG unit has a negative impact, its energy price is lower than the wholesale market price[2]. On the other hand, it is important for investor to know the minimum energy price ($/kWh), that utility will pay to them for their energy production in the specified period of time and specified bus. To reduce the investment risks, the utility should guarantee these prices at the buses in network. Therefore, investors are encouraged to install DGs in pre-determined buses in distribution network.

this paper proposes a method to determine the minimum guaranteed prices at network buses that utility will pay to investor in a time interval, if investor installs DG in that buses. In the time interval, the investment is a dynamical process. Also, different modes of investment with different sequences are considered in proposed method.

PROPOSED METHOD

As mentioned, to reduce investment risk, the utility is willing to guarantee the minimum purchasing prices of DG's energy production at the desired buses for a period of time(as a case: 5 years).

To solve this problem, initially with consideration maximum penetration rate, the optimal location and size of DGs for different penetration rate are determined in several levels with minimizing losses. Then, for each level of penetration rate, the guaranteed prices are determined as follows (it should be noted that utility just guarantees energy purchasing to optimum value at the optimal bus).

At first, with assumption presences of optimal capacity at optimal buses, and with regard to wind turbine (WT) and photovoltaic (PV) technologies, prices are determined according to their 5 years benefits to the utility. The benefits which are considered include loss reduction, pollution reduction, and investments deferral. These prices are equal to minimum prices, because they are determined with consideration of presence of all optimal capacity in the network. Prices are composed of four terms, which are related to wholesale market price, loss reduction, pollution reduction, and investment deferral. To determine loss reduction term of price, at first, the 5 years substation's load duration curve and wholesale market price is divided into 4 levels for each year to reduce the dimension of problem. Then, with load assignment among the buses according to load contribution factors, the expected profit resulting from reduction of electric loss in presence of DGs is calculated. The profits of pollution reduction and investment deferral are determined too. With conversion expected profits to $/kWh and summation it with wholesale market price, the minimum guaranteed price at each level is concluded.

levelization of penetration rate

DG penetration rate is defined as follows.

$$PR = \frac{aggregate capacity of\ DG on\ feeder}{anually\ feeder\ peak\ load}$$

Due to high penetration rate problems, such as protection challenges, feeder congestion, undetectable island and etc, interconnection standard does not allow that penetration rate exceed more than a certain level. On the other hand, due to consideration of 5 years for studies period, the DG investment is dynamical. So, with consideration a maximum penetration rate, it divided into several levels. With division of penetration rate into several levels, actually, the dynamics of investment has been broken into levels with less dynamic behavior. Increasing the penetration rate levels lead to less dynamic at each level. In this paper the maximum penetration rate is considered 30%, and it is divided into three levels (10%, 20%, and 30%).

Optimal sizing and allocation of DG units

The optimal size and location of DGs is determined at each penetration rate level by minimizing energy losses in study time interval for example 5 years. For optimal sizing and allocation of DG units, at first, the maximum allowable DG aggregated capacity (C_T^h) is determined at each penetration level as follows:

$$C_T^h = PR^h.FPL \qquad (1)$$

Where, PR^h is the penetration rate of level-h, and FPL is the maximum feeder load.

Then, due to non-linearity of loss function, C_T^h is divided into k equal level to increase the accuracy of sizing and sitting. After levelization of C_T^h, loss reduction is calculated for each level as follows.

$$\Delta p_{loss}^{i,j} = P_{loss}((j-1).l) - P_{loss}^{i,j}(l) \\ i = 1,2,...,n \qquad j = 1,2,...,k \qquad (2)$$

$$l = \frac{C_T^h}{K} \qquad (3)$$

Where, K is the number of C_T^h levels (more levels lead to more accuracy), n is the number of buses, $P_{loss}((j-1).l)$ is Losses in time interval, when the aggregate DGs installed capacity is $(j-1).l$ kW, $P_{loss}(0)$ is the losses when no DG is installed in network. $p_{loss}^{i,j}(l)$ is the network losses in time interval with injection l kW into bus i, when the aggregate installed capacity of DGs is $(j-1).l$ kW, $\Delta p_{loss}^{i,j}$ is loss reduction for time interval due to injection l kW into bus i, when the aggregate installed capacity of DGs is $(j-1).l$ kW. With respect to equation (2), the optimal bus for l kW injection at level j is determined according to equation (4).

$$OB^J = \{i \,|\, i \in (1,2,...n) \,\&\, \Delta p_{loss}^{i,j} \; is \quad \min\} \; j = 1,2,...,k \qquad (4)$$

Where, OB^j is the optimal bus for l kW injection at level- j. So, the total allocated of capacity to bus i (OC_i), is determined as follow.

$$OC_i = \sum_{\substack{j=1 \\ j | OB^j = i}}^{k} l \qquad (5)$$

The constraint include voltage limits, capacity of feeder limit, and penetration rate limit is considered in accordance with [3]. The optimal sitting and sizing of DGs should be determined for each penetration rate level according to equation (1) to (5).

Minimum guaranteed prices determination

After optimally allocation and sizing of DGs, the guaranteed purchasing prices of energy should be determined so as to lead the investor to install DGs at optimal buses with optimal capacity. It shall be noted that the utility will guarantee energy purchasing at the buses which are optimal. Also the maximum amount of energy that will be guaranteed is equal to the optimal capacity. So, with assumption presence of optimal DGs capacity at optimal buses, the guaranteed prices are determined for each penetration level. These prices (λ_i^h : guaranteed price at bus i at level - h of penetration rate) can be expressed as sum of four terms.

$$\lambda_i^h = \lambda_{net} + \lambda_{loss,i}^h + \lambda_{di,i}^h + \lambda_{en,i}^h \qquad (6)$$

The first term (λ_{net}) is the wholesale market price. The second term (λ_{loss}^h) is associated with DG effect on loss reduction. The third term (λ_{di}^h) is related to effect of DG on investment deferral and the fourth term (λ_{en}^h) corresponds to DG effect on the environment.

Loss benefit pricing

Since the installation of DG will impact on distribution losses, it will have a direct consequence on the utility's profit. If DGs decrease actual network losses, the utilitys' profit will increase, but if the opposite happens, the utility's benefit will decrease. With the purpose to transfer the losses impact to the DGs in the system in the following period, it is necessary to calculate loss coefficients for DGs. These coefficients should determine the contribution of DGs in loss reduction. To calculation of this coefficient, at first, the load duration curve and wholesale market price are divided into 4 levels for each year to reduce the dimension of the problem (figure.1 and figure 2). It shall be noted that 5% load growth is considered for each year and the configuration of network is assumed to be constant in the study. Then, with load assignment among the buses according to load contribution factors, each level benefit is calculated according to equation (7).

$$\lambda_{loss,i}^h = (\lambda_n \sum_{P'=\Delta P}^{k\Delta P} - \frac{\partial loss}{\partial P_{DG,i}}\bigg|_{P_{DG,i}=P'} \times \Delta P) / OC_i \qquad (7)$$

$$\Delta P = \frac{OC_i}{k} \qquad (8)$$

$$\lambda_{loss,i} = \sum_{h=1}^{5\times4} \lambda_{loss,i}^h .P(h) \qquad (9)$$

Where $\lambda_{loss,i}^h$ is the price at bus i at load level- h . $P(h)$ is

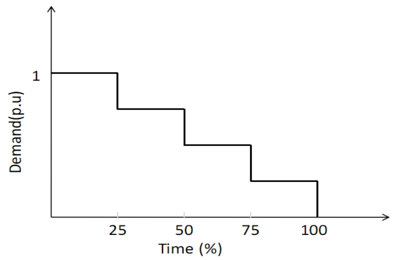

Figure 1: annually load duration curve.

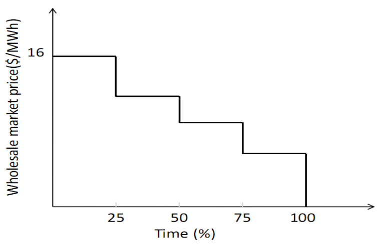

Figure 2: annually wholesale energy price.

the probability of level- h , $\lambda_{loss,i}$ is the expected price which will devote to the DG at bus- i . Due to non-linearity nature of loss changes versa DG power injection, the optimal capacity of DG (OC_i) is divided into k level and marginal loss ($\partial loss / \partial P_{DG,i}$) is calculated for each level [4]. Then the expected price for each DG is determined with respect to equation (7) and (9). According to these equation, if DG has a positive impact on loss reduction, DG get higher revenue with efficient incentive express by nodal pricing.

Investment deferral benefit formulation

Network current peak load ($SD_{\max}$) reaches to its maximum loading ($SS_{\max}$) after N years due to annual load growth. So, the network should be developed to supply load after that year. With installation of DG in network, and assuming the same load growth, network peak demand will be reduced and reached to its' maximum loading after M years. So, the investment in the network will be deferred for $\Delta T = M - N$ years (Figure 3). In the state of presence of no DG in network, equation (10) can be achieved.

$$SD_{\max}(1+\alpha)^M = SS_{\max} \tag{10}$$

After installation of DG,

$$SD_{\max}(1-\gamma)(1+\alpha)^M = SS_{\max} \tag{11}$$

$$\gamma = \frac{OC}{SD_{\max}} \tag{14}$$

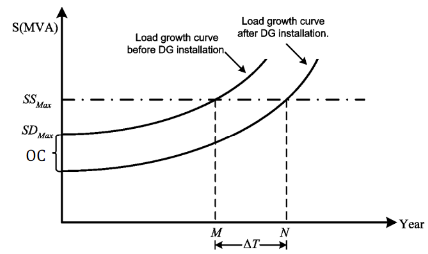

Figure 3: deferral of investment due to DG installation.

$$OC = \sum_{i=1}^{n} OC_i \tag{13}$$

Where α is annually load growth. With regard to equation (10) and (11), equation (14) is achieved as follows.

$$\Delta T = N - M = \frac{\log(\frac{1}{1-\gamma})}{\log(1+\alpha)} \tag{14}$$

The economical benefit of investment deferral is obtained according following equation.

$$ID = C_{invT}\left(1 - \left(\frac{1+\inf r}{1+\operatorname{int} r}\right)^{\Delta T}\right) \tag{15}$$

$$NPV(ID) = ID\left(\frac{1+\inf r}{1+\operatorname{int} r}\right)^{M} \tag{16}$$

Where C_{invT} is the cost of investment, $\inf r$ is the annual inflation rate, $\operatorname{int} r$ is the annual interest rate, and NPV is the function of cost into equivalent present value[5]. The utility devote this benefit to the investors who invest in optimal bus in terms of price as follow.

$$\lambda^h_{di,i} = \frac{NPV(ID)}{5 \times 8760 \times OC} \tag{17}$$

DG enviromental benefit formulation

The implementation of renewable wind and solar energy sources instead of fossil fuels facilitates reductions in air pollution emissions. Taking into account air pollution emissions from the construction and operation stages of power or hydrogen generation plants, and their lifetimes and capacities, the indirect air pollution emissions per unit of produced energy can be calculated (AP_j) [6]. Emission reduction benefit at each hour due to installation of renewable resources can be expressed as:

$$ER = C_{Poll}(P.AP) - C_{Poll}(P.AP - OC.AP) \tag{18}$$

Where, C_{Poll} is the cost of pollution ($/gram.h), P is non-renewable generation before installation of renewable resources. (It is supposed that non-renewable resources use natural gas), AP is air pollution emissions per unit of produced energy (gram/kW), and ER is the benefit of emission reduction ($/h).The utility devote this benefit to the investors who invest in optimal bus in terms of price as follow.

$$\lambda_{en,i}^{h} = \frac{ER}{OC} \quad (19)$$

This term of price encourage the investor to use technology that has more effect on pollution reduction.

CASE STUDY

The proposed method is tested using the 8-bus distribution system showing in Figure. 1 [4]. The line data are provided in the [4]. Load and price levels are considered 8.5, 6, 5.5, 4 (MW) and 35, 25, 20, 16 ($/MWh) respectively. Investment deferral and pollution reduction parameter are in accordance with [5] and [6] respectively. Loads contribution factor are provided on table 1.
Table 2 shows the guaranteed prices and corresponding capacities for three penetration rate levels. Note that these prices are fixed for the period of time under consideration (5 years) for each penetration rate level. It can be seen that guaranteed price at bus-8 is higher than the one of other buses. This is because placement of DG at bus-8 can make a greater contribution to electricity loss reduction. It should be noted that according to proposed method environment and investment deferral term of price ($/kW) are equal for all buses, while the loss term of price is different for different buses. So that for buses which are further away from substation the loss term of price is higher than the others, because placement of DG at that bus can make a greater contribution to electricity loss reduction. Table 2 shows that with increasing the penetration rate, the numbers of buses with guaranteed price is added, because with increasing penetration rate, the numbers of optimal buses for DG installation is increased. Also the guaranteed prices are decreased with increasing penetration rate, because DGs have mutual negative impact on each other energy price; so with increasing penetration rate and consequently increasing numbers of optimal buses for DG installation, the guaranteed prices is decreased.

CONCLUSION

This paper proposes a method to determine the minimum guaranteed purchasing price of RESs energy with consideration their impacts on loss, investment deferral, and air pollution. Because of dynamical behavior of investment, guaranteed prices is determined in three levels of penetration rate (10%, 20%, and 30%). Also utility guarantee the amount of capacity at each bus which are optimal from utility point of view. According to the results the guaranteed prices at buses which are further away from substation is higher than ones at other buses, because DG placement at these buses makes a greater contribution in loss reduction. These pre-determined prices send investment signal to investor to install DG with optimal

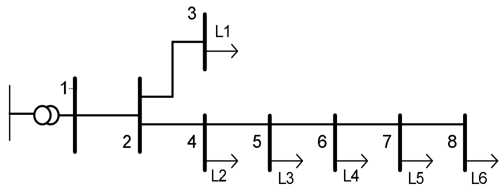

Figure 4: rural distribution network.

Table 1: loads contribution factor.

bus	1	2	3	4	5	6	7	8
LCF	-	-	0.113	0.188	0.198	0.358	0.08	0.05

Table 2: pre-determined guaranteed prices and capacities.

Bus	PR=10%		PR=20%		PR=30%	
	Capacity (kW)	λ ($/MW)	Capacity (kW)	λ ($/MW)	Capacity (kW)	λ ($/MW)
1	-	-	-	-	-	-
2	-	-	-	-	-	-
3	-		-	-	-	-
4	-		-	-	-	-
5	-		-	-	-	-
6	-		680	26.01	1700	25.57
7	470	30.32	760	28.88	770	26.54
8	460	31.43	470	29.98	475	27.99

capacity at optimal buses. It should be noted with increasing penetration rate the guaranteed prices will update to new prices which are correspond to that penetration rate level.

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