Economic Dispatch Problem for Distribution Network Including Wind Turbines and Diesel Electric Generators

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Abstract

In this paper, the economic dispatch problem in a distribution network between the grid, diesel electric generators, and wind turbines has been solved. The scenario tree method to solve the economic dispatch problem is used. Their power probabilities can be calculated by using their cost functions. Powers injected by diesel generators and wind turbines can reduce the power request of the grid and the cost of electricity consumption. In addition, wind turbines and diesel electric generators are placed near the consumers, which result in reduced line losses. Modeling and simulation of diesel electric generators and wind turbines in the 33 ADN distribution network and a local distribution network have been performed. To determine the wind speed of wind turbines, the Weibull probability distribution function is used.

1. Introduction

According to the statistics recorded during recent decades, the world energy consumption has considerably increased. Energy consumption is mainly in the form of electrical energy. Currently, fossil energy sources for electricity production are the main sources. Due to the reduction of fossil fuel resources, in addition to environmental problems, the use of new sources of energy to replace fossil resources has become more important. One of the most important sources of clean, renewable energy is wind energy. However, nature interruptions and unpredictable wind energy are the main problems in the operation of the wind turbines (WT) in distribution networks and power systems. Nevertheless, nowadays WTs are increasingly used to generate electricity in power systems and specifically in distribution networks. Therefore, for the proper management and energy efficiency in an electrical network, suitable probabilistic models of WTs should be employed. However a drawback of WTs is their low reliability. In order to enhance the network reliability, it is reasonable to add more reliable power sources such as diesel electric generators (DEGs) beside the WTs. It should be noted that the price of produced power by DEGs is relatively high. However, DEGs can be used for compensation in the case of any reduction in the power produced by WTs, which can be caused by wind unpredictability, or a rapid increase in the consumer demand. In [1], an optimal power flow algorithm with WTs and DEGs is proposed. This approach led to the total cost minimization which is a result of reduction in the cost of the primary substation power and the cost associated with grid power losses. There are different purposes to add WTs in the distribution networks. Some of important purposes are reducing the cost of electricity, economic dispatch (ED) and energy management. Hetzer et al. created a new model, which adds WTs to the ED problem [2]. In [3] the energy management system provides online set points for four kind renewable generation unit. In [4] a method for generating correlated wind power values is introduced and it is explained how to apply the method when evaluating ED. In [5], an energy dispatch model is presented for a hybrid power supply system. In addition, in that paper a proper management of energy flow from their power supplies when the system is disturbances, is done. A Hybrid Wind Diesel energy system is used in [6]. The Wind turbines role is to reduce diesel consumption.

In this paper, WTs and DEGs are employed together to inject power to the network. At the first stage, an ED is applied between the grid, DEGs and WTs. At the second stage, a probabilistic load flow program is solved because of the presence of WTs and DEGs. Additionally, by using the scenario tree method for wind speeds of WTs, load flow program is utilized for several times. In our method, WTs and DEGs are placed near the loads and a fraction of load demands are supplied by them, therefore the loss of the power in the distribution network is significantly reduced and lower capacity transmission lines can be occupied. Consequently, consumption of the grid power and the electricity cost are reduced. In addition this method leads to slight reduction in the distribution network losses.

2. Problem Formulation

Figure 1 shows a load connected to the grid, a WT, a DEG and the grid to supply it. Probabilistic modeling of the WT, the generator and the power grid is presented in the next sections.
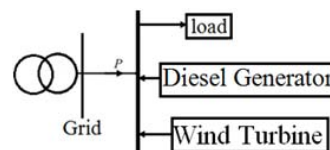

Fig. 1. Load connected to the grid, the presence of the WT and DEG

2.1 Wind generation modeling

Power produced by WTs is highly dependent on the wind speed. There are different approaches to model WTs. In this article, wind speeds are modeled by the Weibull probability distribution function (PDF) [7]. It is shown in Equation (1).

$$PDF(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (1)$$

The coefficients k and c, respectively, are shape and scale factors Weibull PDF of wind speed. Wind speed is shown by v.

The generated power of WT can be determined by speed-power curve. Equation (2) shows speed-power curve of WT.

$$P_i^{wT} = \begin{cases} 0 & if \ v \leq v_{in}^c \ or \ v \geq v_{out}^c \\ \dfrac{v - v_{in}^c}{v_{rated}^c - v_{in}^c} P_{i,r}^{wT} & if \ v \leq v_{in}^c \ or \ v \geq v_{out}^c \\ P_{i,r}^{wT} & else \end{cases}$$

$$(2)$$

$P_{i,r}^{wT}$ is rated power of WT installed on i'th bus, v_{in}^c, v_{rated}^c and v_{out}^c are cut –in, rated and cut-out speeds.
There are three key points in Equation (2): cut-in speed that, it is the turbine first starts to rotate and generate power. Rated speed at which the rated power of the turbine is produced. Cut-off speed that as the speed increases above this, the forces on the turbine structure can damage the rotor. Figure 2 presents WT Speed-Power curves. Equations and the power output curve of the turbine to express the WTs behavior are the same as [8]. The curve shows that, if the wind speed is lower than the cut-in speed or higher than cut-off speed, the power output of the turbine will zero. If the wind speed is higher than cut-in speed and lower than rated speed, the power output of WT will have a linear relationship with speed. This linear relationship is shown in Figure 2.
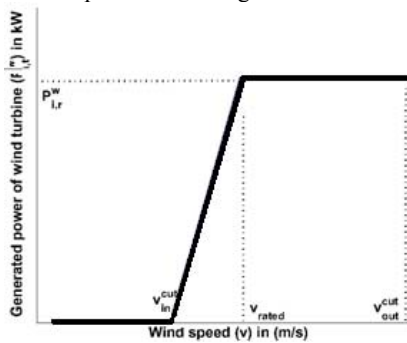

Fig. 2. The curve of Speed-Power WT

As the driving mechanical energy for the WTs is the wind energy which comes for free, the fuel cost is not considered. Only the initial cost for the construction, installation, and maintenance of WTs will be considered. In other words, WTs are more cost effective generators and hence their generated power is fully used.

2.2 Diesel Electric generator modeling

A diesel electric generator consists of a diesel engine and an electric generator, which is used to generate electrical energy. DEGs are set in places without connection to a power grid or as emergency power-supplies in the case of grid failure. In some distribution networks, DEGs support the power grid on peak load conditions. The fuel cost function of DEGs is similar to the conventional cost functions used in power plants fossil fuels. Equation (3) shows the cost of DEGs.

$$C_{DEG,i} = \sum_{i=1}^{N}(a_i + b_i P_{DEG,i} + c_i P_{DEG,i}^2) \qquad (3)$$

$C_{DEG,i}$, $P_{DEG,i}$ and N are the cost of power produced by the DEG, its Output Power and, Number of DEGs respectively. a_i, b_i, c_i are coefficients of the cost of DEG.

2.3. Grid power

Electricity tariffs vary widely from country to country. The price of produced electricity depends largely on the market price of fuel. The amount and timing of electricity usage during the day and in different seasons has a significant impact on setting the electricity price. For example, the price of electricity in Ontario, Canada during the day is divided into three parts: off-peak, mid-peak, and on-peak. Electricity tariffs in these times, are considerably different [9].
The overall cost of the electricity network can be expressed by Equation (4). In this case the price of electricity is also a time-dependent variable.

$$C_{grid} = C_{grid}^{1kW}(t) \times P_{grid} \qquad (4)$$

C_{grid} and P_{grid} are the price and using power electricity- grid power, respectively. $C_{grid}^{1kW}(t)$ is time-dependent tariff

2.4. Economic Dispatch

According to Figure 1, it can be seen that the load is supplied by the WT, DEG, and grid. Equation (5) shows how the load is supported.

$$P_{grid} + \sum_{i=1}^{N} P_{DEG,i} + \sum_{j=1}^{N} P_{WT,j} = P_L + P_{Loss} \quad (5)$$

Variables P_{grid}, P_{DEG}, P_W, P_L, and PLoss are power of the grid, DEGs, WTs, total load demands, and total line losses, respectively.
The cost function of power generated is shown by Equation (6).

Minimize $C_T = C_{grid} + \sum_{i=1}^{N} C_{DEG,i} + \sum_{j=1}^{M} C_{WT,j}$ (6)

Variables C_T, C_{grid}, C_{DEG} and C_{WT} are total cost function, the total cost of grid, DEGs and WTs power generation, respectively.

After installing WTs, no other substantial costs are associated for the WTs, therefore the maximum power produced by WTs is used in the distribution network. It should be noted that the power generated by the WTs is a portion of the entire power demand and the rest of the demand is supplied by the grid and the DEGs. As mentioned earlier, cost of the power generated by WTs is negligible in comparison with the DEGs and network costs. Therefore, Equation (6) can be changed to Equation (7). Similarly, when the wind speed decreases, more power deficit was divided between the DEG and the network.

$$\text{Minimize } C_T = C_{grid} + \sum_{i=1}^{N} C_{DEG,i} \qquad (7)$$

Subject to

$$P_{grid} + \sum_{i=1}^{N} P_{DEG,i} = P_L + P_{Loss} - \sum_{j=1}^{N} P_{WT,j} \quad (8)$$

To optimize the total cost function, Equation (7) can be used by Lagrange function. In order to consider different scenarios of wind fluctuations, the proposed method is used in the scenario tree generation. This method used to minimize Equation (7).

3. Generation Scenario Tree of Wind Speed and Load PDFs

The scenario tree methods can be used for a decision analysis of uncertainty stochastic optimization problems. The overall purpose of tree analysis is to determine the probability of possible states of inputs that one the result of a chosen initiating event. In this method, PDFs of parameter uncertainties are divided into several parts. According to the scenarios for each parameter uncertainties, all possible scenarios are made for the problem. In addition, the probability of each scenario is determined [7].

Figure 3 shows wind speed PDF, which is modeled by several scenarios.

The probability of each possible state of wind speed PDF is shown by Equation (9).

$$\pi_{t,v} = \int_{v1}^{v2} PDF(v)dv \qquad (9)$$

$\pi_{t,v}$ is the probability of each possible state of wind speed PDF. PDF(v) is defined in section (2.1.) by

Equation (1). v1 and v2 are low and high borderlines of each scenario.
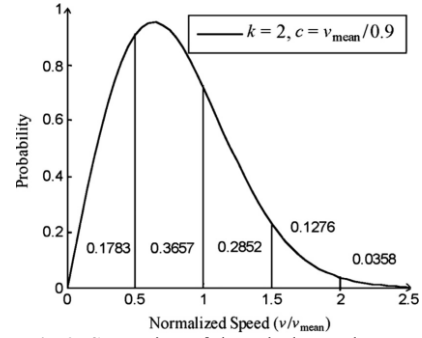

Fig.3. Scenarios of the wind speed PDF

4. Network Characteristics and Numerical Results

Modeling and simulation are applied to the IEEE 33ADN test system [10] and a 77 buses local radial distribution network of Tabriz, Iran. Simulations were carried out according to the paper [11]. Four DEGs and three WTs are added to the network. DEGs on 8, 13, 16, 25 buses, and WTs on buses 14, 16 and 31 are placed. It should be noted that on bus 16, both a WT and a DEG are placed. In the local distribution network, bus 1 is a primary substation bus. This network has 76 load buses, a primary substation bus, and 76 transmission lines. Total active and reactive demands, are 4690 kW and 3854 kVAr respectively. Four DEGs and three WTs similar to IEEE 33ADN test system are added to the network. DEGs on 8, 24, 59, 76 buses, and WTs on buses 14, 36 and 72 are placed.

In this paper, the Weibull parameters of the wind speed in each WT are assumed to be c = 8.78, k = 1.75, similar to [8]. A wind speed histogram of a wind turbine is shown in Figure 6. Power generated by the wind turbines is determined by Equation (2) and its variable values are determined by Equations (10-13).

$$\begin{aligned} v_{in}^{c} &= 3\ m/s; & (10) \\ v_{out}^{c} &= 25\ m/s; & (11) \\ v_{rated} &= 15\ m/s; & (12) \\ P_{r}^{wT} &= 500\ kW; & (13) \end{aligned}$$

All WTs installed in the system are a type DW 52/54 with specification power rated of 500 kW [12]. The power output of the WT is shown in Figure 7.

All DEGs in the system are the Stamford DEGs with type HCI444D. The characteristics of DEGs are P_{max} = 245 kW and Q_{max} = 183 kVAr. The characteristics of generators are shown in Table I [13]. The power generated by the DEGs is 198.4 kW which is obtained by applying

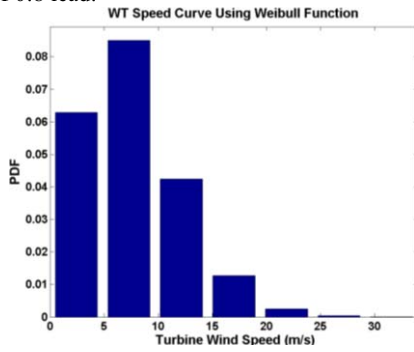the ED equations. DEGs are assumed to have fixed power factor of 0.8 lead.

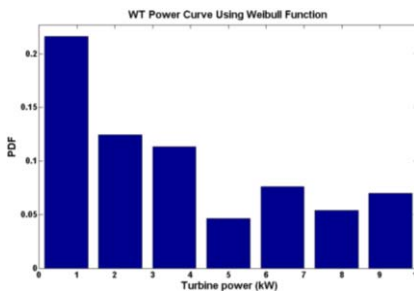**Fig. 6.** The histogram of wind speeds using the Weibull distribution function for the WT

Fig. 7. The histogram of the power output of the WT

Table I. Diesel Electric Generator characteristics

New age/Stamford HCI444D alternator			
Standby		Prime	
kW	kVA	kW	kVA
222	278	245	306

The coefficients of the cost of DEGs Equation (3) are considered as follows.

$$a = 0.0152, \ b = 7.97, \ c = 78.00 \qquad (15)$$

It should be mentioned that in this paper due to the unavailability of the demand prices used in Tabriz network, Ontario, Canada Time-of-Use electricity pricing chart is used to calculate the price of electricity. In this chart, the price of electricity during the day is as follows:

off-peak rate 7.7 cents/kWh, mid-peak rate 11.4 cents/kWh and on-peak rate 14 cents/kWh [9].

At the first step, the demand will be supplied by WTs. Since the power produced by the WTs cannot be predicted precisely, therefore all possible modes of power production of WTs should be considered. The residual demand, which is also a stochastic value, is calculated by the scenario tree method. To distribute the probabilistic remaining-demand between the network and DEGs, a probabilistic ED analysis is performed.

According to the values specified for the output power of WTs, DEGs and network, probabilistic load flow is performed. Thus, the distribution of power in the network and network losses are determined in detail in each scenario. In addition, probability calculations of the consumed power and cost in the grid are performed. Figures 6 to 9 are the histograms of the probability of the active power and losses of both networks, respectively. Grid active power, network losses, and total cost of electricity with and without distributed generators (WTs and DEGs) are shown in Table II.

5. Conclusions

In this paper, a probabilistic load flow was studied. Although the power generated by the WTs has a probabilistic nature, but the power generated by the WTs is cheaper than DEGs and other fossil fuel power plants and hence the maximum power of WTs is used at first place. Subsequently the remaining-demand between DEGs and grid is ED distributed. The scenario tree method is used to calculate the probability of remaining-demand. As a result, the total cost of electricity production is reduced. Also a noticeable reduction in the probabilistic power consumed in the grid is presented. Additionally, line losses are reduced considerably, because the WTs and DEGs generate power near the consumers.

Table II. Grid active power, network losses and total cost of electricity consumption

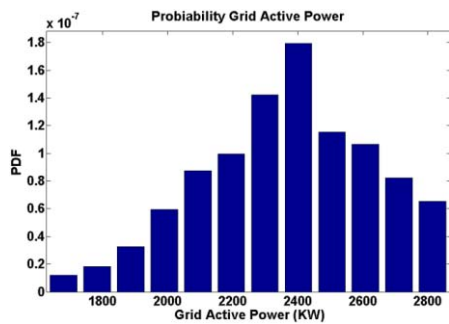| -	Without WTs and DEGs		With WTs and DEGs	
-	33 ADN	77 Buses	33 ADN	77 Buses
Grid Power (kW)	3917	5464	2250 ± 550	3494 ± 680
Total WT Power (kW)	-	-	250 ± 250	250 ± 250
Total DEG Power (kW)	-	-	793.6	793.6
Loss (kW)	203	831	67 ± 24	383 ± 122
Grid Cost (cents)	54838	76496	31500 ± 7700	48916 ± 9520
Total DEG Cost (cents)	-	-	9028	9028
Total Cost (cents)	54838	76496	40528 ± 7700	57944 ± 9520

Fig. 6. the histogram of the probability grid active power in 33 ADN distribution network
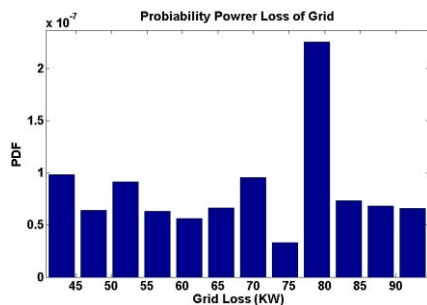

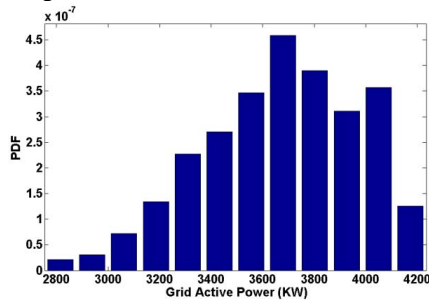**Fig. 7.** the histogram of the probability power loss of grid in 33 ADN distribution network

Fig. 8. the histogram of the probability grid active power in 77 buses local radial distribution network
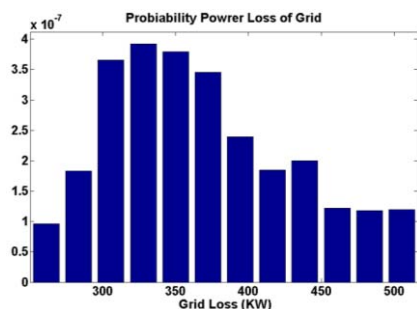

Fig. 9. the histogram of the probability power loss of grid in 77 buses local radial distribution network

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