Economic Dispatch for Microgrid Containing Electric Vehicles via Probabilistic Modeling

Preprint

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Economic Dispatch for Microgrid Containing Electric Vehicles via Probabilistic Modeling

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Abstract—In this paper, an economic dispatch model with probabilistic modeling is developed for a microgrid. The electric power supply in a microgrid consists of conventional power plants and renewable energy power plants, such as wind and solar power plants. Because of the fluctuation in the output of solar and wind power plants, an empirical probabilistic model is developed to predict their hourly output. According to different characteristics of wind and solar power plants, the parameters for probabilistic distribution are further adjusted individually for both. On the other hand, with the growing trend in plug-in electric vehicles (PHEVs), an integrated microgrid system must also consider the impact of PHEVs. The charging loads from PHEVs as well as the discharging output via the vehicle-to-grid (V2G) method can greatly affect the economic dispatch for all of the micro energy sources in a microgrid. This paper presents an optimization method for economic dispatch in a microgrid considering conventional power plants, renewable power plants, and PHEVs. The simulation results reveal that PHEVs with V2G capability can be an indispensable supplement in a modern microgrid.

Index Terms—Transportation electrification, plug-in hybrid electric vehicle, probabilistic distribution model, stochastic model, microgrid, economic dispatch

I. INTRODUCTION

With the trend in transportation electrification (hybrid, battery, and fuel cell vehicles), there is great potential for vehicle-to-grid (V2G) technology. V2G can be an indispensable supplement to the stability (voltage and frequency) and reliability of a microgrid. Three vehicle types are defined in [1] that can supply power back to a microgrid via the V2G method, and the power markets to which they can sell electricity are also defined and explained. Under certain system conditions, V2G can become a practical option in a power market. For instance, V2G will not be a favorable option for baseload power, because baseload power can be dispatched economically with large traditional generators. V2G's greatest short-term objective is for quick-response, high-value electric services. These quick-response electric services are designed to smooth constant fluctuations in both generation (especially wind and solar power plants) and demand sides. Another purpose of the introduction of V2G is to improve the robustness and reliability of a system under unexpected equipment failures. The cost of this quick-response electric service is \$12 billion per year in the United States (5%–10% of total electric cost) [1].

In addition to the advantages of V2G, compared to traditional generators, the short operation hour and high cost per kWh of electric energy of PHEVs suggests that V2G power should be sold only to high-value, short-duration demands in a power market.

Several charging methods are expected to be the mainstream methods for PHEVs in the near future, including centralized charging, self-motivated charging, battery swapping, etc.

Because the charging schedules of PHEVs are not predictable and they are allocated in different areas, the penetration of this large amount of PHEVs' charging load can be a great burden on a microgrid in most conditions.

II. MODELING RENEWABLE ENERGY SOURCES

Solar and wind are two mainstream micropower sources that are widely used in a microgrid. Compared to traditional power plants, they cannot provide a stable output. It is hard to forecast the outputs from both renewable energy sources. Consequently, the economic dispatch for all power sources in a microgrid is difficult to be performed because of the uncertainties induced by the renewable energy sources.

The fluctuations in wind power output are caused by the continuous changes in wind speeds. Similarly, solar power is dependent on radiation from the sun. During daytime, the solar altitude angle and insolation changes seasonally. In this paper, a versatile probability distribution model is used to represent the forecast error for both renewable sources in a microgrid and applied to an economic dispatch problem.

To begin, the probability density function (PDF), cumulative distribution function (CDF), and inverse function of the CDF of a versatile distribution are shown below [2].

$$f(x|\alpha,\beta,\gamma)=\frac{\alpha\beta e^{-\alpha(x-\gamma)}}{(1+e^{-\alpha(x-\gamma)})^{\beta+1}} \tag{1}$$

$$F(x|\alpha,\beta,\gamma)=(1+e^{-\alpha(x-\gamma)})^{-\beta} \tag{2}$$

$$F^{-1}(c|\alpha,\beta,\gamma) = \gamma - \frac{1}{\alpha}\ln(Cs^{-1/\beta} - 1) \quad (3)$$

x: random variable

$\alpha,\ \beta,\ \gamma$: shape parameters

Cs: confidence level

The versatile distribution is a better option to represent the forecast error of renewable energy outputs because

1. Suitable values for shape parameters can be determined from historical data. The root-mean-square error (RMSE) between the actual CDF and the versatile CDF is much smaller than the RMSE between the actual CDF and the Gaussian/Beta CDF [2].
2. The analytic forms for both the CDF and the inverse CDF are available for versatile distribution. This characteristic can facilitate the solution of an economic dispatch problem. It will be further explained in later sections [3].

As an example, data from solar power plants [4] in February is used here. The feasible output time period is from 7 a.m. to 7 p.m. daily. Outside this period, the output is almost zero because of low solar radiation. The forecast span is set at 15 days. Specifically, 15-day actual output data from a 100-kW solar power plant from February 1 to February 15 is utilized to generate suitable shape parameters for the versatile distribution model. The detailed procedure is explained in the following section.

1. The actual CDF is generated from 15-day solar power plant data;
2. Ten to 20 characteristic points are selected from actual CDF;
3. nlinfit/lsqcurvefit functions in MATLAB are used for curve fitting according to the characteristic points.

The curve-fitting results are shown in Figure 1 to compare the performance of two different functions. The power base is set at 100 kW in this paper.

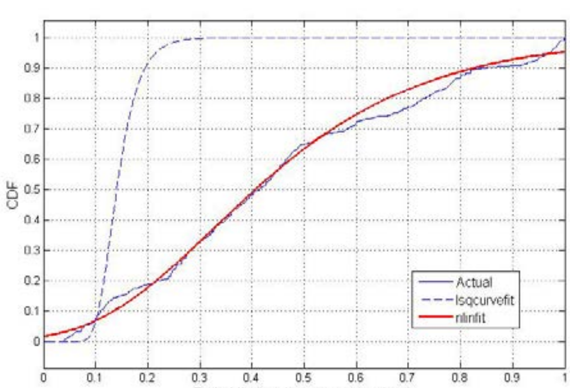

Figure 1. Different performances of curve-fitting functions

It is clear that the CDF generated by nlinfit is more accurate than the CDF curve by lsqcurvefit. To verify the accuracy of the curve fitting, the actual PDF and versatile PDF are illustrated in Figure 2.

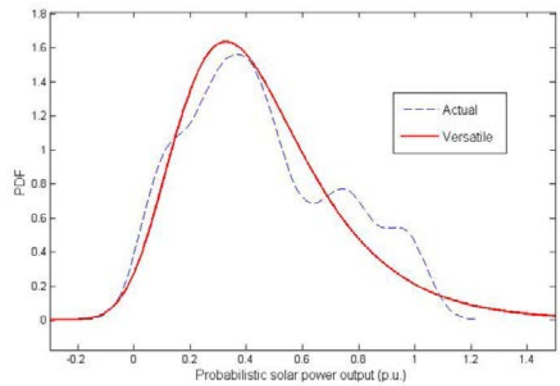

Figure 2. Actual PDF compared to versatile PDF

The versatile PDF fits the actual PDF curve reasonably well. The performance and accuracy are both verified in this case. Similarly, the versatile distribution can be applied to a wind power plant to represent the forecast error in a 15-day forecast span. The simulation results based on actual data [4] are shown in Figure 3 and Figure 4.

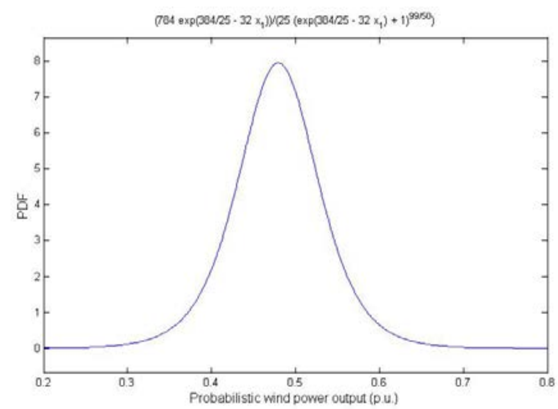

Figure 3. Wind farm versatile PDF

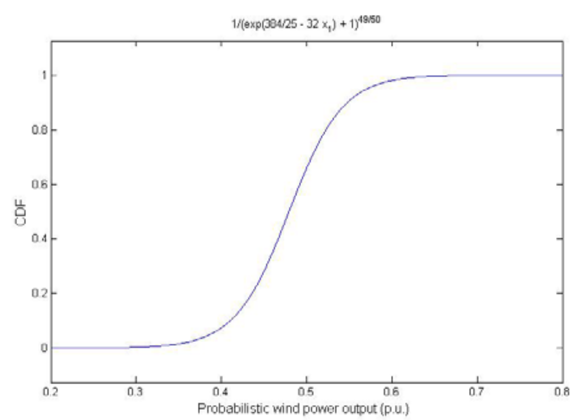

Figure 4. Wind farm versatile CDF

1) Wind farm generation cost

Because of the accuracy limitation of wind power prediction, the actual output power can be higher or lower than the predicted output. This inaccuracy will result in an operational penalty. The three components of wind generation costs (direct cost, overestimation cost, and underestimation cost) are calculated in the following set of equations [3].

$$C_{w,j}(w_j) = d_{wj} w_j \tag{4}$$

$C_{w,j}$: cost function of wind farm j

w_j: scheduled power of wind farm j

d_{wj}: direct cost coefficient of wind farm j

$$\begin{aligned} C_{pw,j}(w_{av,j} - w_j) &= k_p (w_{av,j} - w_j) \\ &= k_p \int_{w_j}^{w_{r,j}} (x - w_j) g w_j(x) dx \end{aligned} \tag{5}$$

$C_{pw,j}$: underestimation cost function of wind farm j

$w_{av,j}$: actual available power of wind farm j

k_p: underestimation cost coefficient

$w_{r,j}$: installed capacity of wind farm j

$gw_j(.)$: PDF of the output of wind farm j for the forecast values

$$\begin{aligned} C_{rw,j}(w_j - w_{av,j}) &= k_r (wj - w_{av,j}) \\ &= k_r \int_0^{w_j} (w_j - x) g w_j(x) dx \end{aligned} \tag{6}$$

$C_{rw,j}$: overestimation cost function of wind farm j

k_r: overestimation cost coefficient

2) Solar farm generation cost

Similarly, the solar power plant shares the same pattern of generation costs as the wind power plant. However, there is some difference between solar power and wind power. The feasible output period of a solar power plant is dependent on the actual solar radiation period. In this paper, according to actual data [4], the feasible output period is set from 7 a.m. to 7 p.m. for a 15-day forecast span. The set of cost functions are shown below.

$$C_{s,k}(s_k) = d_{sk} s_k \tag{7}$$

$$C_{ps,k}(s_{av,k} - s_k) = k_p \int_{s_k}^{s_{r,k}} (x - s_k) g s_k(x) dx \tag{8}$$

$$C_{rs,k}(s_k - s_{av,k}) = k_r \int_0^{s_k} (s_k - x) g s_k(x) dx \tag{9}$$

$C_{s,k}$: cost function of solar power plant k

s_k: scheduled power of solar power plant k

d_{sk}: direct cost coefficient of solar power plant k

$C_{ps,k}$: underestimation cost function of solar power plant k

$s_{av,k}$: actual available power of solar power plant k

$s_{r,k}$: installed capacity of solar power plant k

$gs_k(.)$: PDF of the output of solar power plant k for the forecast values

$C_{rs,k}$: overestimation cost function of solar power plant k

III. Vehicle to Grid (V2G) Modeling

3.1 V2G Capacity prediction

The high amount of charging loads of PHEVs can be a great burden to the whole power grid. However, via the V2G method, the huge energy in PHEVs' batteries can supply power back to the grid if necessary. Especially in a microgrid circumstance, V2G can serve as an energy storage device to smooth out the fluctuations in solar and wind generation. To begin, some characteristics of PHEVs need to be discussed:

1. PHEVs are commuting devices for their owners. The charging/discharging procedure needs to be conducted with no conflict to the owner's daily driving behavior. So the available time period and capacity is limited to the corresponding individual user.

2. The randomness of the charging/discharging behavior of each PHEV must be considered.

These characteristics make V2G technology not totally reliable. A great number of PHEVs charging/discharging without planning and order not only increases the pressure on the grid but also wastes electricity in the end. As a result, research about V2G charging/discharging capacity is essential for control strategies.

In the beginning of PHEV development, the total scale and amount of PHEVs was very limited. Compared to a whole electric power system, the impact could even be neglected. However, a microgrid system has comparatively low installed renewable energy capacity. Thus, the impact of PHEVs cannot be overlooked. The PHEV control center can reasonably utilize the response from all the PHEVs in certain areas for peak shaving and valley filling to increase the efficiency of energy usage.

In a microgrid, power generators can be divided into components such as a conventional power plant, fuel cell, PV, wind turbine, bio energy, etc. To some extent, a microgrid can be represented as a combination of several micro energy resources. In the circumstances of a microgrid, the system setting needs to take PHEVs into consideration. In the following, a conventional power plant, wind power plant, solar power plant, and PHEV are all included. Hence, a comprehensive optimized strategy can be developed.

3.2 Versatile distribution model of V2G in a microgrid

Based on the simulation results from [5] and [6], the versatile distribution model of V2G in a microgrid is developed. Because of the uncertainty of V2G output, the cost functions consist of three parts: direct cost, underestimation cost, and overestimation cost. The PDF of V2G output from 15 Chevy Volts is shown below.

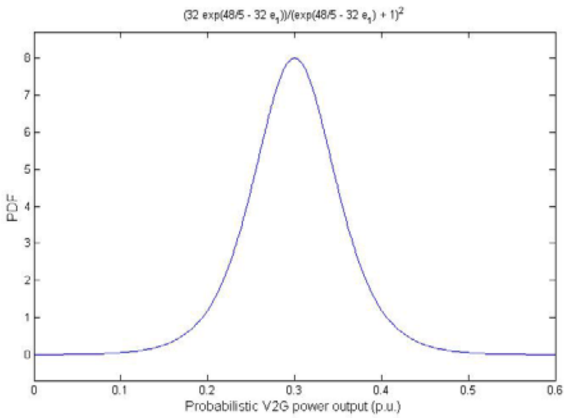

Figure 5. Versatile PDF of V2G power output

IV. CASE STUDY: ECONOMIC DISPATCH IN MICROGRID

In a microgrid, the goal is to minimize the total generation cost. C_{Total} is set as the subtotal generation cost of the whole microgrid system. In this example, C_{Total} includes the generation cost of a conventional power plant, wind power plant, solar power plant, and the V2G of PHEVs.

The simulation is based on the standard IEEE 9-bus test system. The system includes 3 PQ busses and 9 transmission lines. Detailed system parameters are shown below. Bus 1 is the reference bus.

Table 1. Transmission lines parameters

Values are in per unit and based on 100 MWA					
Element#	From bus	To bus	R	X	Half-line charge
1	7	8	0.0085	0.072	0.0745
2	8	9	0.0119	0.1008	0.1045
3	7	5	0.032	0.161	0.153
4	9	6	0.039	0.17	0.179
5	5	4	0.01	0.085	0.088
6	4	6	0.017	0.082	0.079
7	2	7	0	0.0625	1
8	9	3	0	0.0586	1

Table 2. Bus parameters

All power values are in MW and Mvar								
Bus#	Bus type	V	Pg	Qg	Pl	Ql	Qmin	Qmax
1	2	1.04	-	0	0	0	0	0
2	2	1.025	163	0	0	0	-100	130
3	2	1.025	85	0	0	0	-70	50
4	1	1	0	0	0	0	-	-
5	1	1	0	0	125	50	-	-
6	1	1	0	0	90	30	-	-
7	1	1	0	0	0	0	-	-
8	1	1	0	0	0	0	-	-
9	1	1	0	0	0	0	-	-

Objective function (cost minimization)

$$\begin{aligned}\min C_{Total} &= \sum_{i=1}^{I} C_i(p_i) + \sum_{j=1}^{J} C_{w,j}(w_j) + \sum_{k=1}^{K} C_{s,k}(s_k) + \sum_{l=1}^{L} C_{e,l}(e_l) \\ &+ \sum_{j=1}^{J} C_{pw,j}(w_{av,j} - w_j) + \sum_{k=1}^{K} C_{ps,k}(s_{av,k} - s_k) + \sum_{l=1}^{L} C_{pe,l}(e_{av,l} - e_l) \\ &+ \sum_{j=1}^{J} C_{rw,j}(w_{av,j} - w_j) + \sum_{k=1}^{K} C_{rs,k}(s_{av,k} - s_k) + \sum_{l=1}^{L} C_{re,l}(e_{av,l} - e_l)\end{aligned} \tag{10}$$

Constraints:

$$\sum_{i=1}^{I} p_i + \sum_{j=1}^{J} w_j + \sum_{k=1}^{K} s_k + \sum_{l=1}^{L} e_l = L \tag{11}$$

$$p_{\min,i} \le p_i \le p_{\max,i} \tag{12}$$

$$0 \le w_j \le w_{r,j} \tag{13}$$

$$0 \le s_k \le s_{r,k} \tag{14}$$

$$0 \le e_l \le e_{r,l} \tag{15}$$

$$\sum_{i=1}^{I} r_{u,i} \ge \sum_{j=1}^{J} (w_j - w_{av,j}) + \sum_{k=1}^{K} (s_k - s_{av,k}) \tag{16}$$

$$\sum_{i=1}^{I} r_{d,i} \ge \sum_{j=1}^{J} (w_{av,j} - w_j) + \sum_{k=1}^{K} (s_{av,k} - s_k) \tag{17}$$

L is the system demand, e_r is the installed capacity of the PHEV fleet l, and $r_{u,i}$ and $r_{d,i}$ are the up and down regulation reserves provided by a conventional power plant, i. These two constraints represent that the over-/underestimation of wind power plant output must be covered by the up/down regulation reserves of a conventional power plant. The cost function of a conventional power plant is

$$C_i(p_i) = a_i p_i^2 + b_i p_i + c_i \tag{18}$$

where a_i, b_i, and c_i are fuel cost coefficients of a conventional power plant, i.

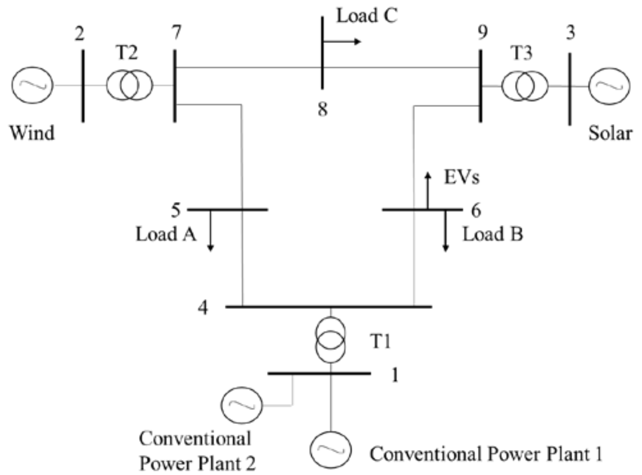

Figure 6. Modified IEEE 9-bus system with PHEVs and DGs

As shown in Figure 6, a 100-kW wind power plant is connected to Bus 2. On Bus 3, a 100-kW solar power plant is connected to it. Two conventional power plants are both connected at Bus 1. The output capacity of both conventional power plants is 100 kW. In this case study, 15 PHEVs are connected to Bus 6 as the V2G energy source. The rated output is 3.5 kW per vehicle. All generation variables are expressed in per unit. The system power base is 100 kW. The direct cost coefficient of wind power and solar power is 2 \$/MWh. For V2G, the direct cost coefficient is 10 \$/MWh. The underestimation and overestimation cost coefficients, k_p and k_r, are set to 1.5 \$/MWh and 3 \$/MWh [7]. The up regulation reserve is 0.2 per unit. The down regulation reserve is 0.1 per unit. The confidence levels, c_u and c_d, are both set to 0.95. The fuel cost coefficients and output limits for both conventional power plants are listed in Table 3. The parameters of the versatile distribution for wind, V2G, and solar are given in Table 4.

Table 3. Parameters of conventional power plants

	a (\$/h)	b (\$/h)	c (\$/h)	Pmin (p.u.)	Pmax (p.u.)
CPP 1	100	200	10	0.4	1
CPP 2	120	150	10	0.4	1

Table 4. Parameters of wind, V2G, and solar

	alpha	beta	gamma
Wind	32	0.98	0.48
V2G	32	1	0.3
Solar	4.48	55.98	-0.57

Because the inverse CDF of the versatile distribution has an analytical form, the optimization problem can be linearized and solved by sequential linear programing. A detailed procedure can be found in [2] and [3]. The simulation results are shown in Figure 7. P1 and P2 are two conventional power plant outputs. S1 is the solar power plant output. E1 is the V2G output. X1 is the wind power plant output. There are two obvious load peaks: around noon and around evening. The load peak at 8:00 a.m. is 2.9 per unit. And the peak load of the day is 3.37 per unit at 6:00 p.m. From Figure 8, it can be determined that V2G participates in power generation at 6 p.m., 7 p.m., and 8 p.m. These time points are also during the load peak period in which V2G can be a quick, responsive power source to dispatch in a microgrid.

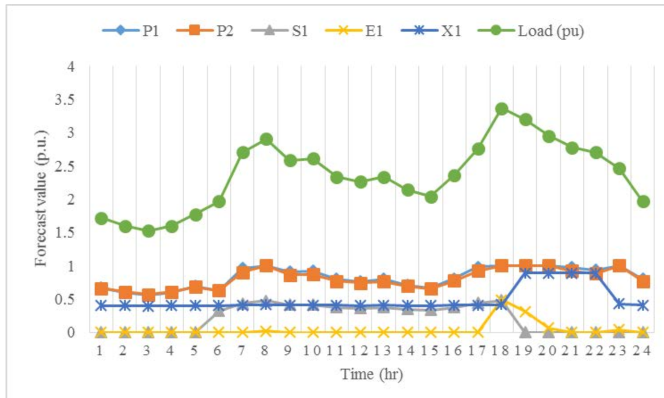

Figure 7. Forecast values for all micro power sources

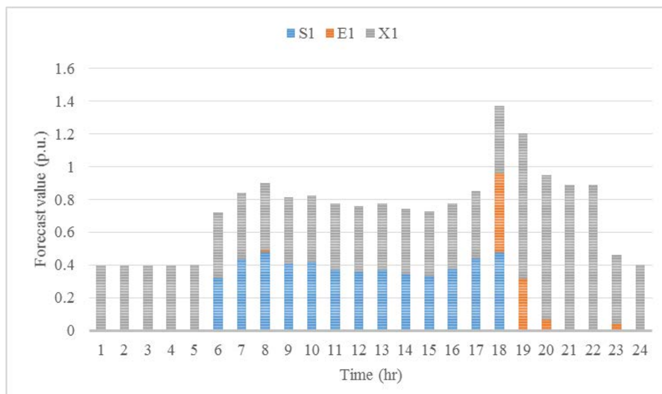

Figure 8. Output value of wind, V2G, and solar

V. Conclusion

With the growth of the amount of PHEVs, charging load of PHEVs would surely present a great pressure on the distribution level grid. Meanwhile, with the help of V2G method, PHEVs can be a reliable power source in microgrid.

In this paper, a versatile distribution model is utilized to forecast the output error for a solar power plant, wind power plant, and V2G. Then the probabilistic distribution models are applied to an economic dispatch problem in a microgrid. The IEEE 9-bus case study results revealed that V2G can serve as a quick, responsive energy source to accommodate peak loads. As a result, the power quality in a microgrid can be improved.

In conclusion, transportation electrification in a microgrid will surely become more and more critical in distributed generation. Because the main energy sources in a microgrid of the future are wind and solar power plants, the microgrid system will always need a reliable and responsive power source. V2G can be a favorable option with the increasing penetration level of PHEVs. On the other hand, V2G is able to help a microgrid become more independent of an external power grid.

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