# ECONOMIC DISPATCH OF ACTIVE DISTRIBUTION NETWORK CONSIDERING RENEWABLE ENERGY UNCERTAINTIES

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## ABSTRACT

*In general, Active Distribution Network (ADN) serves as a foundation of demand-side management which enables the involvement of electricity consumption in the dispatch of electricity generation. In order to achieve the economic dispatch of ADN, the potential risk of renewable energy uncertainties need to be taken into consideration during the dispatch. By combining Chance-Constrained Programming (CCP) with Genetic Algorithm (GA), ADN is able to keep a balance between its economic profit and the potential risk. Through proper allocation of ADN's demand-side curtailment and the power exchange between the main power grid, ADN is able to avoid the influence of renewable energy's uncertainties and promote the stability of distribution network as well as the accommodation of renewable energy. The risk-balanced ADN economic dispatch model proves to be an effective solution to the coordination problem between renewable energy uncertainties and the stability requirement of the distribution network.*

## INTRODUCTION

Traditional coal and petroleum based energy structure has been suffering through environmental pollution and resource exhaustion. As an effective solution to the current obstacle, distributed renewable energy resources especially solar photovoltaic and wind power generation have gained significant developments. Unlike traditional large scale wind and photovoltaic generation corporation, the distributed renewable energy resources are located among the demand-side as a supplement to the power shortage and blackout [1]. Despite the convenience of the application of renewable energy in demand-side, the uncertainties involved within renewable energy's output contributes to the instability of distribution network which may lead to the frequent fluctuation and power unbalance. Thus in order to improve the stability of distribution network, ADN need to take the mentioned uncertainties into its curtailment schedule and minimize the side-effect of the uncertainties through proper allocation of the controllable load curtailment. Although the curtailment of controllable load may lead to the decrease of ADN's economic profit, the punishments for power unbalance and blackout may even make the situation worse. Compared with additional payment for power exchange in the main power grid, the compensations for controllable load curtailment seem to be more economical acceptable.

Also, the integration of renewable energy's uncertainties into the calculation model of ADN improves the ADN's accommodation status of renewable energy which reduces the unnecessary curtailment of renewable energy when the distribution network is suffering through power overproduction.

Compared with micro-grid and virtual power plant, the emergence of ADN enables us to achieve a coordinated operation between the local electricity demand and the renewable energy resources [2]. Unlike traditional utility company which solely focuses on the stable operation of distribution network, ADN modifies the traditional unidirectional electricity power flow into a controllable bidirectional power flow which reinforces the participation of demand-side into the power market. Through the proper usage of the integrated renewable energy, ADN is more flexible and sensitive in demand-side management [3].

## CALCULATION MODEL

Renewable energy especially wind and photovoltaic have been widely studied and modeled at present. However, none of the current model is applicable and accurate in all situations due to the fluctuation nature of the mentioned resources. In order to simulate the output of distributed wind and photovoltaic generators, this paper uses Weibull Distribution and Beta Distribution in the construction of the calculation model.

### Wind Output Model

Among the proposed wind output calculation model, Weibull Distribution is the most frequently used and adopted calculation method which reviews the fluctuation nature of wind. The probability density function of Weibull Distribution model is defined as follows [4].

$$f(v|c,k)=\frac{k}{s}\left(\frac{v}{s}\right)^{k-1}e^{-\left(\frac{v}{s}\right)^{k}} \qquad (1)$$

Where k and s separately represents scale and shape parameters in Weibull Distribution. And v stands for the wind speed. By using Monte Carlo Simulation method, we can easily approach to a modeled wind speed forecast in the day ahead market. The relationship between the output of the wind generators and the wind speed can be defined as follows.

$$P_w=\begin{cases} P_{w,r} & v_r\le v\le v_{co} \\ P_{w,r}\frac{v-v_{ci}}{v_r-v_{ci}} & v_{ci}\le v\le v_r \\ 0 & v<v_{ci}\ or\ v>v_{co} \end{cases} \qquad (2)$$

Where $P_{w,r}$ and $v_r$ represents the rated output and rated speed of wind generators; $v_{ci}$ and $v_{co}$ stand for the cut-in and cut-out speed of wind generator;

As for the uncertainties of wind power, we consider the wind generator's forced outage rate $\delta_w$ and the wind output forecast error $\varepsilon_w$ which is subject to Normal Distribution $N(0,\sigma_w^2)$ , by using a uniform distribution parameter $\xi_w$~U(0,1) which is compared with the settled parameter $\delta_w$, we can transform the random number $\xi_w$ into a binary parameter as follows [5].

$$\xi_w = \begin{cases} 0 & \xi_w \le \delta_w \\ 1 & \xi_w > \delta_w \end{cases} \tag{3}$$

If $\xi_w = 0$, we assume the wind generator is out of service. Otherwise, we presume the wind generator to operate normally.

## Photovoltaic Output Model

As for the calculation model of photovoltaic generator, we presume to use the Beta Distribution to simulate the fluctuations of photovoltaic output. The Beta Distribution probability density function can be defined as follows [6].

$$f(P_{pv} \mid \alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left(\frac{P_{pv}}{P_{pv,\max}}\right)^{\alpha-1}\left(1-\frac{P_{pv}}{P_{pv,\max}}\right)^{\beta-1} \tag{4}$$

Where $\alpha$ and $\beta$ are the shape parameters of Beta Distribution; $P_{pv,max}$ represents the maximum output of photovoltaic generator. As for the simulation of photovoltaic generator's uncertainties, we use the same method which has been presented in the Wind output model section.

The output forecast error of photovoltaic generator is defined as $\varepsilon_{pv}\sim N(0,\sigma_w^2)$ and the forced outage rate $\delta_{pv}$ is handled by the same method in wind simulation where we define a random parameter $\xi_{pv}$ and compare it with $\delta_{pv}$ to modify it into a binary parameter which reviews the status of the photovoltaic generator during our simulation schedule.

## ADN Dispatch Model

Unlike traditional utility company which focuses on the operation and stability of distribution network, ADN focuses on the economical and stable arrangement of local demand response. In order to neutralize the side-effect of renewable energy's integration, the objective function of ADN aims at the minimum cost of operation considering the uncertainties involved with renewable energy which can be defined as follows.

$$\min Cost = \sum_{t\in T}\{p_{b,t}\times P_{b,t} - p_{s,t}\times P_{s,t} + C_w(P_{w,t}) + C_{pv}(P_{pv,t}) + C_{cl}(P_{cl,t})\} + \pi_{risk}\times risk + \pi_{cur}\times P_{cur} \tag{5}$$

$$P_{b,t}\times P_{s,t} = 0 \tag{6}$$

Where $P_{b,t}$ and $P_{s,t}$ represent the power exchange between the distribution network and the main grid which are constrained to be unidirectional during a certain dispatch period defined in Equation (6). $P_{w,t}$ and $P_{pv,t}$ are the estimated output of wind and photovoltaic generators. $P_{cl,t}$ represent the curtailment power of controllable load which is managed by ADN.

As for the estimated output power of renewable energy, in this model, we permit the curtailment of renewable energy in order to meet with the emergence of power imbalance. However, this curtailment should result in the economic punishment issued by Independent System Operator (ISO). Thus the definition of the curtailed power can be expressed as follows.

$$P_{cur} = P_{w,t} + P_{pv,t} - \bar{P}_{w,t} - \bar{P}_{pv,t} \tag{7}$$

Where $\bar{P}_{w,t}$ and $\bar{P}_{pv,t}$ are the real output of renewable energy respectively. The choice of punishment parameter $\pi_{cur}$ in Equation (5) is controlled by ISO on behalf of the management of renewable energy integration.

According to the current research in ADN, the cost function for renewable energy generation is usually considered linear correlation with the output of the mentioned power. Also, the compensation for the use of controllable load is defined as linear correlation with the power curtailed. By using proper price guidance, ADN is able to modify the controllable load from peak hours into valley hours which benefits the accommodation of renewable energy and the stability of the power grid as well.

Due to the deviations in the output forecast of renewable energy as well as the threat of generator outages, the operation of ADN needs to make a balance between its economic profit and its potential risk cost. In order to identify the potential risk faced by ADN during its dispatch, the model introduces the definition of Expected Energy Not Supplied (EENS) as a measurement of the potential risk [7].

$$EENS = \sum_{t\in T}\{[(1-\xi_w)\bar{P}_{w,t} + \xi_w\varepsilon_{w,t} + (1-\xi_{pv})\bar{P}_{pv,t} + \xi_{pv}\varepsilon_{pv,t} + \varepsilon_{load,t}] - P_{cl.t}\} \tag{8}$$

The definitions of the parameters have been explained in the previous sections. In the calculation of EENS, we presume that ADN will try to balance the power supply with its controllable load which will be curtailed if the estimated renewable power is not enough or the renewable energy generator is suddenly outage.

If ADN is not able to balance the power with its limited controllability in controllable load, ADN will have to purchase additional power from main grid in real-time market which is quite expansive. Here, we use $\pi_{risk}$ as a punishment parameter for the purchased additional power.

## MATHMATICAL SOLUTION

In order to solve the above problem, we introduce a combined CCP-GA calculation method. Unlike traditional GA calculation method, CCP-GA calculation method combines the advantages of both CCP and GA calculation methods which enables the ADN to have a better understanding of the potential risk brought by the renewable energy.

The traditional CCP can be defined as follows [8]. Where $\bar{f}$ represents the objective function of CCP and $g_j(x,\zeta)$ stands for the constraint towards the object.

$$\max \bar{f}$$

$$s.t. P_r\{f(x,\zeta) \geq \bar{f}\} \geq \mu \qquad (9)$$

$$P_r\{g_j(x,\zeta) \leq 0, j = 1 \ldots n\} \geq \rho_j$$

Based on the mentioned ADN calculation model, the proposed CCP-GA calculation method could be applied to the model by adopting the following constrains.

$$\bar{f} = Cost \qquad (10)$$

$$P_r\{P_{cl.t} - [(1-\xi_w)\bar{P}_{w,t} + \xi_w \varepsilon_{w,t}] - [(1-\xi_{pv})\bar{P}_{pv,t} + \xi_{pv}\varepsilon_{pv}] \geq \varepsilon_{load}\} \geq \rho \qquad (11)$$

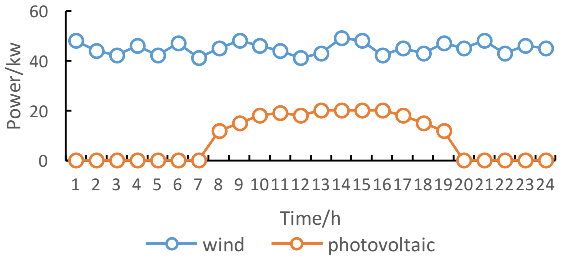
Where $\rho$ represents the confidence coefficients of CCP. The change of $\rho$ may result in the variations of ADN's dispatch of controllable load. By choosing proper $\rho$, ADN is able to minimize the potential risk while if $\rho$ is too high, ADN has to spare more controllable load reserved for the possible change of renewable energy output. As a consequence, ADN will have limited ability left for the handling of load shift which may result in the high cost for power purchase from main grid in peak hours. On the other hand, if $\rho$ is too low, ADN may be able to complete the load shift from peak hours to valley hours while ADN is vulnerable facing the change of renewable energy output which may result in the high cost for additional power purchase from main grid in real-time market [9].

Thus the influence of $\rho$ upon the dispatch of ADN is obvious and influential which deserved to be proper chosen and analyzed in the case study. Also, in order to have a better analysis of the potential risk that ADN faces with, we use average EENS($\overline{EENS}$) in the calculation instead. The average EENS is achieved by multiple random simulations during the risk analysis [10].

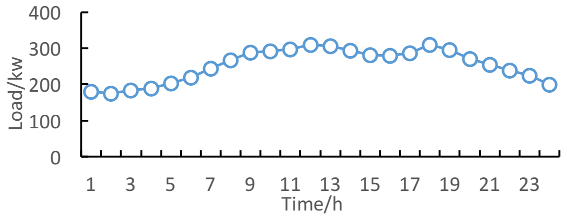
## CASE STUDY

In case study, we apply the mentioned model and the CCP-GA calculation methods into a real active distribution network model in China. The estimated output curves of photovoltaic and wind generators during the whole dispatch cycle are presented in Fig 1(a). In addition, the total load curve of the distribution network is in Fig 1(b) and the peak-valley electricity prices are shown in Fig 1(c).

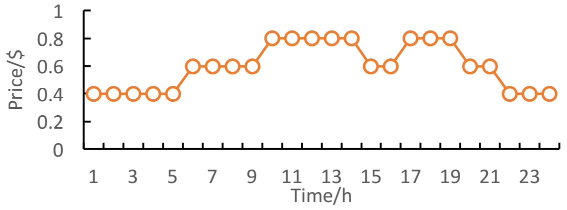
In the case study, we presume the controllable load capacity of ADN is 50kw which requires the compensation fee of curtailment at the price of 0.15$/kw. In addition, the curtailed capacity need to be fulfilled during the dispatch cycle.



(a)



(b)



(c)

Fig 1. Basic Information about the ADN

In order to analysis the influence of ADN's controllable load curtailment, we conclude the result of ADN's dispatch via different cases as follows.

Table 1.ADN's economic results among different cases

| situation | Total cost/$ | Risk cost/$ | Cost without risk/$ |
|---|---|---|---|
| Case1 | 3016 | 0 | 3016 |
| Case2 | 2888 | 0 | 2888 |
| Case3 | 3295 | 279 | 3016 |
| Case4 | 3130 | 198 | 2932 |

In Table1, where case1 represents the situation that ADN's controllable load wasn't curtailed while case2 allows ADN to curtail the controllable load during the dispatch schedule. However, in the first two cases, we assume the risk cost is 0. As a contrast, in case3 and case 4, we take the risk cost when the coefficient $\rho = 0.9$ into consideration. The dispatch results of ADN are also presented in Fig 2.

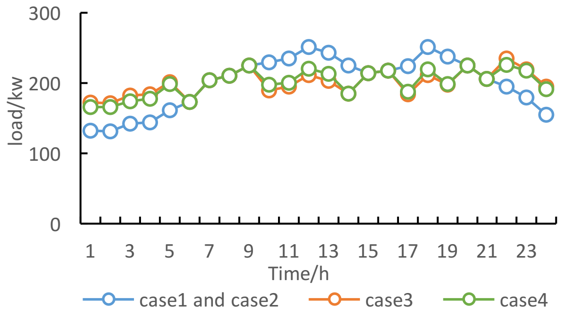


Fig 2. ADN's dispatch results in different cases

From the comparison in Table1 and Fig 2, we can find out that ADN's proper curtailment of controllable load is economic profitable which could reduce the economic cost of ADN in a large degree. Also, the potential risk cost is crucial in the dispatch of controllable load. If not handled well, the uncertainties in renewable energy will contribute to the economic loss for ADN. Through case

3 and case 4, we can figure out that, proper dispatch of controllable load could greatly reduce the influence of renewable energy.

## CONCLUSION

The application of CCP-GA calculation methods into the dispatch of ADN is proven to be useful especially in solving the curtailment problem of controllable load. However, the choose of the calculation parameters of CCP-GA is crucial which may lead to ADN's economic loss as a result of its curtailment overreact. Also, the case study results prove that the curtailment of ADN's controllable load could significantly reduce the influence of renewable energy's uncertainty. Through proper schedule of controllable load's curtailment, ADN is able to achieve the risk-balanced economic operation of the distribution network which neutralizes the influence of renewable energy's uncertainty while maximizes the accommodation of renewable energy resources. The contribution of this article is that the proposed risk-balanced ADN economic model as well as its CCP-GA calculation method are proven to be applicable and serve as a foundation for future ADN operation problem in smart grid environment.

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