Time-varying Characteristic Based Load Forecasting Method for Distribution Network with High Penetration DGs

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SUMMARY

Middle-term and long-term load forecasting is important for planning of distribution network. With high penetration DG (distributed generation) integrated into network, the net load demand of HV/MV transformers become more complicated, load forecasting encounters greater challenge than ever. Volatility and intermittency of wind and solar power has greatly influenced the load characteristics. In the past, when planners evaluated the affect, DG was usually simply seemed as “negative load” without concerning its time-varying characteristic, which would cause inaccurate results.

A new load forecasting method for distribution network with DGs is proposed in this paper, which concerns time-varying characteristic of DG output power. Firstly, we get the conventional spatial load forecasting results. Then, using Monte Carlo simulation, we get the time-varying characteristic of DG. Lastly, superposing time-varying characteristics of conventional load and DGs, we can get the net-load forecasting result for distribution network.

In this paper, the superposition method of time-varying characteristics is proposed to deal with diversity problem of maximum loads. In the basis of historical yearly 8760 hour-varying data, we can get yearly time-varying curves for different types of load, which can be superposed into total load time-varying curve for the forecast area.

In Monte Carlo simulation of DG output power, the probability models of wind speed and
illumination intensity are analyzed firstly. Then, the power characteristic models of DG are proposed. For the forecast area, we need enough weather data to establish the probability models of wind speed and illumination intensity for different months or seasons, then we can get yearly time-varying curves of DG output power using Monte Carlo simulation.

Using the superposition method of time-varying characteristics, we can superpose time-varying curves of conventional load and DG output power. The new superposed curve we get is net-load time-varying characteristic for distribution network. The volatility and seasonality of DG output power are contained in the net-load time-varying curve, which is very useful for distribution network planners.

At last, we choose power grid of a North China city to illustrate the use of the mentioned method. From analysis results, we find the new technology valid and effective. Concerning greatly changed load characteristic of distribution network, we also give some special recommendations on DSM (Demand Side Management) and allocation of ESS (Energy Storage System) for this grid.

KEYWORDS
Load forecasting; Distribution network; Distributed generation; Time-varying Characteristic Superposition method; Monte Carlo simulation.

1. Introduction
Middle-term and long-term load forecasting is important for planning of distribution network[1-3]. With high penetration DG (distributed generation) integrated into network, the net load demand of HV/MV transformers become more complicated, therefore load forecasting encounters greater challenge than ever. Volatility and intermittency of wind and solar power generation has greatly influenced the load characteristics[4-5].

In recent years, distribution network planning concerning DGs is studied in many literatures[6-8], but they usually take maximum load as forecasted load, not concerning the influence by DGs time-varying output. Literature[9-10] propose new load modeling methods concerning DGs, literature[11] introduces short-term net load forecasting method for busbar containing DGs. Till now, there are few research on middle-term and long-term load forecasting concerning DGs.

A new load forecasting method for distribution network with DGs is proposed in this
paper, which concerns time-varying characteristic of DG output power. Firstly, we get the conventional spatial load forecasting results. Then, using Monte Carlo simulation, we get the time-varying output characteristic of DG. Lastly, superposing time-varying characteristics of conventional load and DGs, we can get the net-load forecasting result for distribution network.

2. Main Procedures of Time-varying Characteristic Based Load Forecasting Method

Time-varying Characteristic Based Load Forecasting Method includes following key steps:

1. Data collection which includes city and regional planning schemes, historical load data, typical load characteristics, historical weather data, scale and layout of distributed generations in future, etc.

2. Yearly time-varying load curves forecasting for different types of load, for which we need historical load data, and typical characteristics for different types of load. The forecasting methods are studied in many literatures[1-3], which are not main research points in this paper.

3. Monte Carlo simulation for yearly time-varying curves of DG output power, which is based on historical weather data and the probability models of wind speed and solar irradiation intensity.

4. Yearly time-varying load curves forecasting concerning DGs, which is based on superposition method.

3. Monte Carlo simulation of DG output power

In this paper, we analyze two types of DG, wind and PV power.

3.1 Probability model of wind speed and Output characteristic of wind generator

Many studies show that wind speed generally follows Weibull distribution[14]. The distribution function and probability density function are as follows:

\[
F(v) = P(V \leq v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right]
\]

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

In the above equation, \(v\) is wind speed; \(k\) and \(c\) are two parameters of Weibull distribution, \(k\) is the shape parameter, \(c\) is the scale parameter, the two parameters can be calculated by average wind speed \(\mu\) and standard deviation \(\sigma\):
The mathematical function relationship between wind generator output and wind speed is approximately shown as follows:

\[ k = \left( \frac{\sigma}{\mu} \right)^{1.085}, \]

\[ c = \frac{\mu}{\Gamma(1+\frac{1}{k})}, \]

\[ P = \begin{cases} 
0 & 0 \leq V \leq V_i \\
A + B \times V + C \times V^2 & V_i \leq V \leq V_r \\
P_r & V_r \leq V \leq V_o \\
0 & V \geq V_o 
\end{cases} \]

\[ A = \frac{1}{(V_i - V_r)^2} \left[ V_i(V_i + V_r) - 4V_iV_r \left( \frac{V_i + V_r}{2V_r} \right)^3 \right] \]

\[ B = \frac{1}{(V_i - V_r)^2} \left[ 4(V_i + V_r) \left( \frac{V_i + V_r}{2V_r} \right)^3 - 3(V_i + V_r) \right] \]

\[ C = \frac{1}{(V_i - V_r)^2} \left[ 2 - 4 \left( \frac{V_i + V_r}{2V_r} \right)^3 \right] \]

In the above equation, \( V \) is wind speed, \( V_i \) is start-up wind speed, \( V_r \) is rated wind speed, \( V_o \) is cut-off wind speed, \( P_r \) is rated power of wind generator.

### 3.2 Probability model of solar irradiation intensity and Output characteristic of PV

Solar irradiation intensity generally follows Beta distribution\[15\]. The probability density function is as follows:

\[ f(s) = \begin{cases} 
\frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} s^{(\alpha-1)}(1-s)^{\beta-1} & 0 \leq s \leq 1, \alpha \geq 0, \beta \geq 0 \\
0, & \text{else} 
\end{cases} \]
In the above equation, \( s \) is solar irradiation intensity, \( f(s) \) is probability intensity of solar irradiation intensity, \( \alpha \) and \( \beta \) are two parameters of Beta distribution which can be calculated by average solar irradiation intensity \( \mu \) and standard deviation \( \sigma \):

\[
\beta = (1 - \mu)\left(\frac{\mu(1 + \mu)}{\sigma^2} - 1\right)
\]

\[
\alpha = \frac{\mu \beta}{1 - \mu}
\]

The output power of PV can be calculated as follows:

\[ P = S \times A \times \eta \]

In the above equation, \( P \) is output power of PV, \( S \) is solar irradiation intensity (kW/m²), \( A \) is area of single PV module (m²), \( \eta \) is rated transform efficiency of PV. Suppose there are \( n \) PV modules working, the total output power of PV is \( nP \).

3.3 Monte Carlo simulation

For the forecast area, we need enough weather data to establish the probability models of wind speed and illumination intensity for different months or seasons. Then, based on these probability models and capacity of DGs, we can get yearly time-varying curves of DG output power using Monte Carlo simulation.

4. Load forecasting concerning DGs

4.1 Superposition method of time-varying characteristics

To deal with diversity problem of different types of load, we usually use load coincidence factor to sum up maximum loads. However, the method accuracy will be weakened when types of load become more and the forecast area become larger.

The superposition method is based on time-varying characteristics. In the basis of historical yearly 8760 hour-varying data, we can get yearly time-varying curves for different types of load, which can be superposed into total time-varying load curve for the forecast area[12-13].

The superposition method is as follows:

\[ p(t) = \sum_{i} p_i(t) \]

\[ p_i(t) = P_{max} \times f_i(t) \]

In the above equation, \( p(t) \) is yearly time-varying load curves of the planning area; \( p_i(t) \) is yearly time-varying load curves of different types of land; \( P_{max} \) is the forecasted
maximum load of different types of land; \( f_i(t) \) is the typical time-varying load curves of different types of land.

Distributed generations also have diversity problem. Similarly, the superposition method can be also used to solve this problem. In general, the superposition method relies on large amount of data, which can help us know the overall characteristic of different objects.

4.2 Superposition of load and DG output

Using the superposition method of time-varying characteristics, we can superpose time-varying curves of conventional load and DG output power. The new superposed curve we get is net-load time-varying characteristic for distribution network (8760 hours). The volatility and seasonality of DG output power are contained in the net-load time-varying curve, which is very useful for distribution network planners. The net-load time-varying curve can be get as follows:

\[
P(t) = P_0(t) - \sum P_{DG}(t)
\]

In the above equation, \( P(t) \) is net-load time-varying curve concerning DG, \( P_0(t) \) is load time-varying curve, \( P_{DG}(t) \) is DG output time-varying curve.

5. Case Study

5.1 Basic information

To illustrate the proposed method, we have applied it in a 100km2 North China city, which will have 150 wind turbines and 1200000 PV panels integrated into network in the future.

5.2 Yearly time-varying load curves forecasting

Based on historical load data and regional planning scheme, we can get maximum load forecasting results for different types of load. Then, based on typical characteristics of different types of load, we can get forecasted yearly time-varying load curves of the city shown in Fig.1.
Fig. 1 Yearly time-varying load curve of the city

5.3 Monte Carlo simulation for yearly time-varying curves of DG output
Based on average weather condition of the city and the probability models of wind speed and solar irradiation intensity introduced before, we can get yearly time-varying curves of DG output.

5.4 Yearly time-varying load curve forecasting concerning DGs
Based on time-varying curves of conventional load and DG output we get in 5.2 and 5.3, we can use superposition method to get yearly time-varying net-load curve, which is the load forecasting result concerning DGs. The forecasted load curve and load duration curve are shown in Fig. 2 and Fig. 3.

5.5 Recommendations on DSM and allocation of ESS
From above figures, we can see that integration of high penetration DGs greatly changes load characteristic of distribution network. However, we can also see the maximum load is almost same before and after the integration, which means that the investment of the grid expansion constructions wouldn’t be obviously cut down. Concerning this problem, we can take some special ways such as DSM and ESS to improve the load characteristic. We can use time-of-day pricing DSM scheme and optimize the allocation of ESS to shift load. Load duration curve concerning DGs and DSM is shown in Fig. 4, from which we can see the maximum load is cut down for about 5%.
Fig. 2 Yearly time-varying net-load curve concerning DGs

Fig. 3 Load duration curve comparison before and after integration of DGs

Fig. 4 Load duration curve concerning DGs and DSM
6. Conclusion
This paper proposed a new time-varying characteristic based load forecasting method for distribution network with DGs. Based on large amount of historical load and weather data, this method can effectively evaluate the influence caused by volatility and intermittency of DG output. Load forecasting result can also help us find new ways to improve yearly and daily load characteristics.

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