IMPACT OF WIND SPEED CORRELATION ON PLANNING AND OPERATION OF DISTRIBUTION NETWORK

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ABSTRACT

This paper establishes the model of wind speed correlation (WSC) by inverse Nataf transformation. The impacts of WSC on distribution network operation and maximum installed capacity of wind power are investigated by Monte Carlo simulation and chance constrained programming method. A new definition of wind power penetration is proposed. Finally, conclusions are duly drawn.

INTRODUCTION

Plenty of wind turbines are connected to the distribution network (DN). Wind turbines connected to the same DN are relatively geographically close, which makes the wind speed have strong correlation and wind power be spatially correlated [1]. Wind speed correlation (WSC) will strength the synchronization (increase and decrease simultaneously) of different wind turbines' power output and increase the fluctuation of total wind power output (WPO). When the wind power penetration (WPP) is high, the impacts of WSC on the planning and operation of DN should be considered.

WSC has been investigated in some technical literatures, and the researches mainly focus on three aspects: wind speed and power prediction [2], reliability evaluation of power system [3], and probabilistic load flow [4]. These researches have shown the importance of taking into account WSC when several wind farms are connected to the same power system. For example, the loss of energy expectation of RBTS considering WSC is 22.3% higher than the value without considering WSC [3].

In this paper, inverse Nataf transformation is adopted to establish the WSC model. The impacts of WSC on DN operation are studied by Monte Carlo simulation method. And the maximum installed capacity of wind power (MICWP) considering WSC is investigated by chance constrained programming method. Due to the limitation of traditional definition of WPP, a new one is proposed.

WSC MODELING

Nataf transformation

Nataf transformation is a mathematical model for the transformation from the correlated original space to mutually independent standard normal one [5], [6]. It requires the marginal cumulative distribution function (CDF) of each random variable and their correlation matrix, which are easy to be obtained in engineering applications. When the marginal CDF $F_i(v_i)$, i=1,…,n of correlated wind speed vector $\mathbf{V}=[v_1,v_2,\ldots,v_n]$ are available, a correlated standard normal variable (SNV) vector $\mathbf{X}=[x_1,x_2,\ldots,x_n]$ can be obtained by marginal transformation

$$x_i = \Phi^{-1}(F_i(v_i)) \quad i=1,\ldots,n \tag{1}$$

where $\Phi(\bullet)$ is the CDF of SNV.

The relationship between correlation coefficient ρ_{0ij} of vector $\mathbf{V}$ and correlation coefficient ρ_{1ij} of vector $\mathbf{X}$ can be expressed as

$$\rho_{0ij} = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \left(\frac{v_i-\mu_i}{\sigma_i}\right)\left(\frac{v_j-\mu_j}{\sigma_j}\right) \times \phi_2(x_i,x_j,\rho_{1ij})dx_i dx_j \tag{2}$$

where ρ_{0ij} and ρ_{1ij} are the elements of correlation matrixes $\boldsymbol{\rho}_{\mathbf{V}}$ and $\boldsymbol{\rho}_{\mathbf{X}}$, μ_i and σ_i are, respectively, the mean and standard deviation (SD) of wind speed v_i, and $\phi_2(x_i,x_j,\rho_{1ij})$ is the two-dimensional standard normal probability density function of zero means, unit SD, and correlation coefficient ρ_{1ij}.

For the complexity of calculating (2), Liu and Der Kiureghian [7] presented the empirical formula to approximately determine the solution of (2) for Weibull distribution

$$\rho_{1ij} = D(\rho_{0ij})\rho_{0ij} \tag{3}$$

where the expression of $D(\rho_{0ij})$ is

$$D(\rho_{0ij}) = 1.063 - 0.004\rho_{0ij} - 0.2\left(\frac{\sigma_i}{\mu_i}+\frac{\sigma_j}{\mu_j}\right) - 0.001\rho_{0ij}^2 + 0.337\left(\left(\frac{\sigma_i}{\mu_i}\right)^2+\left(\frac{\sigma_j}{\mu_j}\right)^2\right) + 0.007\rho_{0ij}\left(\frac{\sigma_i}{\mu_i}+\frac{\sigma_j}{\mu_j}\right) - 0.007\left(\frac{\sigma_i}{\mu_i}\right)\left(\frac{\sigma_j}{\mu_j}\right)$$

In most engineering applications, $\boldsymbol{\rho}_{\mathbf{X}}$ is positive definite. So it can be decomposed by Cholesky decomposition.

$$\boldsymbol{\rho}_{\mathbf{X}} = \mathbf{G}_{\mathbf{X}}\mathbf{G}_{\mathbf{X}}^T \tag{4}$$

where $\mathbf{G}_{\mathbf{X}}$ is an inferior triangular matrix.

The correlated SNV vector $\mathbf{X}$ can be transformed into a new vector $\mathbf{Y}=[y_1,y_2,\ldots,y_n]$ of independent ones by

$$\mathbf{Y} = \mathbf{G}_{\mathbf{X}}^{-1}\mathbf{X} \tag{5}$$

The correlated wind speed vector $\mathbf{V}$ is transformed to the independent SNV vector $\mathbf{Y}$ by (1)~(5), and this is the positive process of Nataf transformation.

Generation of correlated random numbers

The random numbers of correlated wind speed can be generated by inverse Nataf transformation when CDFs $\mathbf{F}(\mathbf{V})$ and correlation matrix $\boldsymbol{\rho}_\mathbf{V}$ are given. The basic steps are as follows.

1) Generate the random numbers $\mathbf{Y}_s$ of vector $\mathbf{Y}$.
2) Obtain the correlation matrix $\boldsymbol{\rho}_\mathbf{X}$ of correlated SNV vector $\mathbf{X}$ by (3). Decomposing this matrix by Cholesky decomposition can get $\mathbf{G}_\mathbf{X}$.
3) Generate the random numbers $\mathbf{X}_s$ of vector $\mathbf{X}$ by (6).

$$\mathbf{X}_s = \mathbf{G}_\mathbf{X}\mathbf{Y}_s \tag{6}$$

4) Generate the correlated random numbers $\mathbf{V}_s$ of wind speed $\mathbf{V}$ by marginal transformation.

$$\mathbf{V}_s = \mathbf{F}^{-1}(\boldsymbol{\Phi}(\mathbf{X}_s)) \tag{7}$$

CASE STUDY CONDITIONS

The IEEE 33-bus system has been modified to include wind generation, as shown in Fig. 1. There are four small wind farms, and the installed capacity of each wind farm is 0.5MW. The same Weibull distribution, with scale and shape parameters, equal to 8 and 2.2, respectively, is used to model the wind speed at four wind farms. And the power curve of each wind turbine is described by the linear model, which means the power curve between the cut-in speed and rated speed is linear. The probability model of each load is assumed to be normal distribution with means equal to the original values, and SD of 5% with respect to such mean values. The voltage magnitude of slack bus is set to 1.035p.u.. All four wind farms are correlated with correlation coefficient p.

The random numbers of correlated wind speed are firstly generated by the method proposed in the previous section and subsequently transformed into power production to obtain the random numbers of wind power. The impacts of WSC on distribution network operation and MICWP are then investigated.

IMPACTS OF WSC ON DN OPERATION

Impacts of WSC on WPO

The relationships between WPO at bus 18 and WSC are shown in Fig. 2. WSC has little influence on the mean of WPO. On the contrary, the SD of WPO is almost proportional to WSC. The capacity factor of wind power is 0.433. When WSC coefficient p is increased from 0.1 to 0.9, the mean of WPO has a 0.47% increase, while SD has a 38.64% increase. Fig. 3 shows the histograms and cumulative distribution curves (CDC) of WPO with different WSC coefficients. When the WSC coefficient is larger, the probabilities of low power output section and high power output section of total WPO are larger.

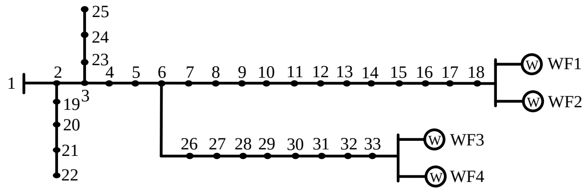

Fig. 1 Modified IEEE 33-bus system

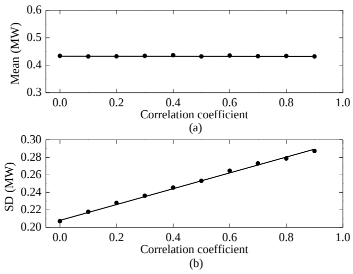

Fig. 2 Relationships between WPO at bus 18 and WSC

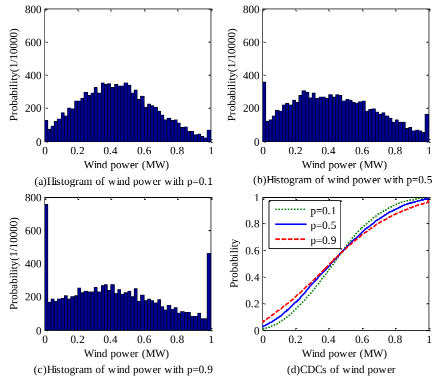

Fig. 3 WPO at bus 18 with different WSC coefficients

For example, when the WSC coefficients are 0.1, 0.5 and 0.9, the probabilities of WPO lower than 20% of installed capacity at bus 18 are 15.15%, 20.50% and 24.58%, respectively.

Impacts of WSC on bus voltage

Fig. 4 shows the voltage distribution curve considering the variation of load demand and WPO. The voltage of bus 18 and bus 33 is affected by WPO most apparently. Fig. 5 illustrates the relationships between bus 18 voltage and WSC. Mean of voltage is barely impacted by WSC, while SD of voltage is almost proportional to WSC. There is a 63.57% increase of voltage SD when WSC coefficient is increased from 0.1 to 0.9. The probabilistic density curves (PDC) and CDCs of bus 18 voltage with different WSC coefficients are shown in Fig. 6. When the WSC coefficient is larger, the probabilities of low voltage section and high voltage section are larger. For example, the probabilities of bus 18 voltage lower than 0.96p.u. are 8.90%, 14.98% and 20.76%, respectively, when the WSC coefficients are 0.1, 0.5 and 0.9. The impacts of WSC on line flow are similar.

Impacts of WSC on network loss

Fig. 7 shows the relationships between network loss and WSC, which are similar to the impacts of WSC on WPO.

Although there is a 107.21% increase of network loss SD when WSC coefficient is increased from 0.1 to 0.9, the network loss is not always increased or decreased with WSC. The reason is that the maximum difference of network loss mean is 11.22kW, and the one of network loss SD is only 8.03kW. The PDCs and CDCs of network loss with different WSC coefficients are shown in Fig. 8.

IMPACTS OF WSC ON MICWP

Voltage quality is one of the most important issues on DN operation. Due to the randomness and fluctuation of WPO, the bus voltage of DN with wind power may have certain probability to be out of limit. EN 50160 states that the probability of voltage out of limit must be lower than the requirements. With the constraint of voltage quality, MICWP with different WSC coefficients is studied, which can be described by (8). The constraints contain load flow equation W=f(X) and probability constraint of voltage out of limit.

$$\max(n_1+n_2)$$
$$s.t.\begin{cases} W=f(X) \\ P(V_i<0.95\cup V_i>1.05)<5\%, i=1,2,..,33 \end{cases} \quad (8)$$

where n_1 and n_2 is the number of wind turbines with installed capacity of 50kW at bus 18 and bus 33, respectively.

The chance constrained programming method based on genetic algorithm is adopted to solve (8). The results are shown in Table 1. Fig. 9 shows the impacts of WSC on MICWP, mean and SD of WPO. The MICWP is different at different buses, and the line parameters and load levels will affect MICWP. The MICWP is impacted by WSC apparently. When WSC coefficient is increased, the MICWP and mean of WPO are decreased, while the SD of WPO is still increased, and the relationships among them are nonlinear. When WSC coefficient is increased from 0.1 to 0.9, the MICWP has a 11.28% decrease, and SD of WPO still has a 14.85% increase. If the impacts of WSC on MICWP are not considered, the voltage quality of some buses will be difficult to meet the requirements. The probabilities of voltage out of limit at bus 18 and bus 33 are shown in Fig. 10, with n_1 and n_2 equal to 53 and 98, respectively. WSC has apparent influence on the installed capacity planning of wind power in DN. It is more reasonable to select the DN planning scheme with wind power when WSC is considered.

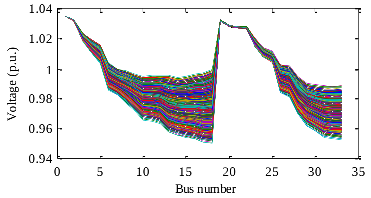

Fig. 4 Voltage distribution curve of modified IEEE 33-bus system

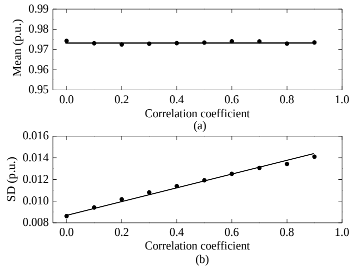

Fig. 5 Relationships between bus 18 voltage and WSC

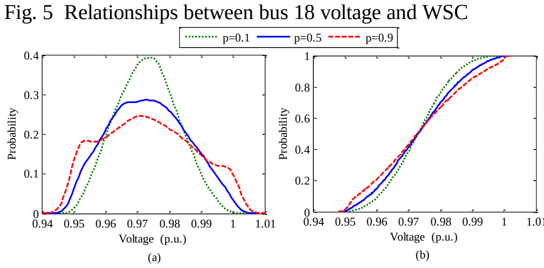

Fig. 6 PDCs and CDCs of bus 18 voltage with different p

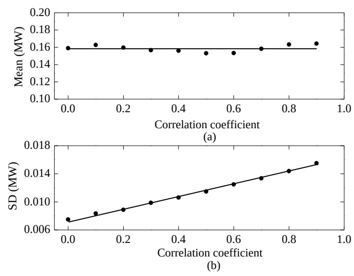

Fig. 7 Relationships between network loss and WSC

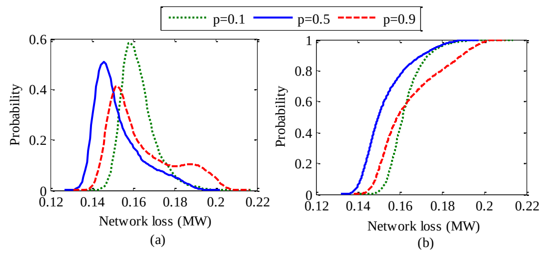

Fig. 8 PDCs and CDCs of network loss with different p

Table 1 MICWP with different WSC coefficients

WSC	n_1	n_2	Total	WSC	n_1	n_2	Total
0	53	98	151	0.5	47	91	138
0.1	52	96	148	0.6	46	90	136
0.2	50	94	144	0.7	46	89	135
0.3	48	93	141	0.8	45	89	134
0.4	48	92	140	0.9	45	88	133

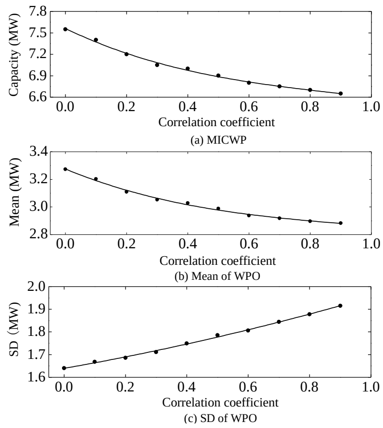

Fig. 9 Impacts of WSC on MICWP, mean and SD of WPO

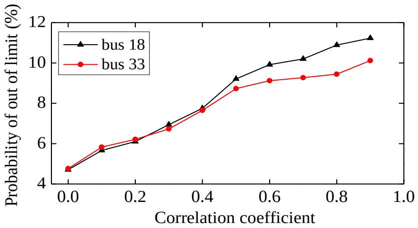

Fig. 10 Probability of bus voltage out of limit

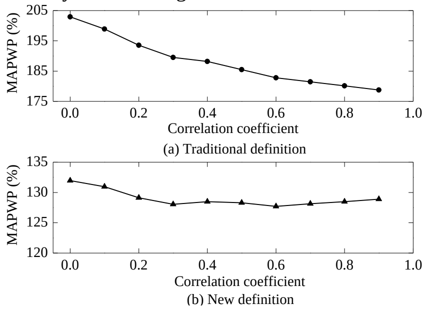

Fig. 11 Relationships between different MAPWP definitions and WSC

Table 2 Comparison of two definitions through MAPWP

Definition	Maximum (%)	Minimum (%)	Maximum difference (%)	SD (%)
η_0	202.96	178.76	24.20	7.75
η_1	131.96	127.70	4.26	1.30

The actual WPO is different from its installed capacity. Wind speed fluctuation, and power curve and control strategy of wind turbine have apparent influence on the actual WPO. The impacts of WPO on power system operation are not only related to its installed capacity, but also other factors, for example, the fluctuation of WPO. Traditional definition of WPP is the rate of wind power installed capacity and system total load demand, shown by (9). This definition ignores the randomness and fluctuation of WPO, and can't characterize the impacts of WPO on power system operation very well. A new definition of WPP is proposed by (10).

$$\eta_0 = \frac{P_{installed}}{P_{load}} \times 100\% \qquad (9)$$

$$\eta_1 = \frac{aP_{installed} + bP_{sd}}{P_{load}} \times 100\% \qquad (10)$$

where $P_{installed}$ is the installed capacity of wind power, P_{load} is the system total load demand, P_{sd} is the SD of WPO, a and b are the weight coefficients.

Fig. 11 shows the relationships between maximum allowable penetration of wind power (MAPWP) of two definitions and WSC, and a and b are equal to 0.433 and 1.0, respectively. Table 2 illustrates the comparison of the two definitions through MAPWP. Although the MICWP is different when WSC coefficients are different, the impacts of WPO on DN operation are almost the same. The maximum difference and SD of new definition are 4.26% and 1.30%, respectively. And the ones of traditional definition are 24.20% and 7.75%. It illustrates the new definition of WPP is more robust and reasonable to characterize the impacts of WPO on the operation of power system.

CONCLUSIONS

Inverse Nataf transformation is adopted to establish the WSC model. The impacts of WSC on DN operation and MICWP are investigated. A new definition of WPP is proposed. The conclusions are as follows:

1) WSC has important impacts on the operation of DN. The mean values of WPO, bus voltage, line flow and network loss are barely impacted by WSC, while the SD values are almost proportional to WSC. The WSC will strength the synchronization of different WPO, which increases the fluctuation of total WPO, and further affects the operation of DN.

2) The MICWP is affected by WSC with nonlinear relationship. When WSC is increased, MICWP is decreased and the SD of WPO is still increased. The MICWP without considering WSC is optimistic, which makes some bus voltage not to meet the voltage quality requirements.

3) The new definition of WPP takes the randomness and fluctuation of WPO into account. It can characterize the impacts of WPO on power system operation more reasonably.

4) Considering WSC can help to access the impacts of multiple wind farms on the operation of DN more reasonably, and select better DN planning scheme and operation modes.

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