Optimization of Wind Farm Collection Line Structure under Symmetrical Grid Fault*

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Abstract: A power-transmission collection line is connected to each wind turbine of a wind farm and then connected to the incoming switchgear at the low-voltage side of the booster station at a certain distance. Therefore, the grouping of the wind turbines in the wind farm determines the layout of the lines and affects the line impedance. The line structure and composition of the wind farm are analyzed, and the relationship between the impedance of the collection line and reactive power generated by the wind turbine at low-voltage ride through is derived. We conclude that the smaller the equivalent impedance of the wind farm collection line structure is, the greater the reactive power at the wind farm collection line point is. In addition, the economic aspect of the collection line needs to be considered in the design. The economic aspect and impedance values have contrasting characteristics. Therefore, according to the condition of minimum impedance and optimized economic aspect, an optimization model of a wind-farm collector-circuit structure is proposed. The optimal structure of the wind farm collector circuit is calculated using the Monte Carlo method, and the theoretical analysis is verified by simulation.

Keywords: Wind farm, symmetrical grid fault, collection line, optimization model

1 Introduction

In recent years, wind energy, as a developing clean-energy source, has driven related industries, continuously promoted the development of national economy, and played a very important role in environmental improvement[1-3]. With the continuous improvement in wind-power generation (WPG) technology, the WPG types have transitioned from a constant-speed WPG system (WPGS) to a variable speed WPGS. Among them, the variable-speed WPGS realizes decoupling of the generator and grid and improves the utilization efficiency of wind energy. It is the mainstream system of the WPGS[4]. The wind turbines of a variable-speed WPGS include doubly fed and permanent-magnet direct drives. Compared with the doubly fed wind turbines, permanent-magnet direct drives eliminate the need for gearboxes. Therefore, they offer the advantages of high power-generation efficiency, high reliability, low operating and maintenance costs[5]. In addition, with regard to the converter of the permanent-magnet direct-drive wind turbine, it converts the variable frequency and voltage generated by the motor into a usable constant-frequency voltage using a control system. Four types of topologies are available. (1) Uncontrolled rectification at the machine side using a grid-side pulse width modulation (PWM) inverter. (2) Machine-side uncontrolled rectification + boost using a grid-side PWM inverter. (3) Machine side adopts phase control rectification using a grid-side PWM inverter. (4) Double PWM-controlled power converter. The fourth topology is the most extensive because PWM rectification can reduce the stator-current harmonic content of the generator compared with the other topologies. Thus, it reduces the copper and iron losses of the generator. The PWM rectifier can also provide an almost sinusoidal current, thus reducing the harmonic current at the generator side[6-7].

Three laying-out methods are available to transmit electrical energy for the collection-line connection the wind-turbine inside the wind farm. (1) Using overhead lines. (2) Using the cables buried directly. (3) Using the combination of overhead lines and cables[8]. The three laying-out methods depend on the wind-farm conditions and economic factors. For example, if more farms and residential areas are available, overhead lines are preferable. If the environment in the area is not conducive or the site is located near certain important sites, it is better to use cable directly buried in view of the beauty[9]. To study

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the influence of the collection-line layout on the low-voltage ride through (LVRT), we need to ensure that the types of collection lines under the different laying-out methods are consistent. This study adopts the method of laying overhead lines. Because the voltage generated by a wind-farm wind turbine is relatively small, when electric power is directly delivered using the voltage generated by the wind turbine, a large amount of power is lost, and the efficiency is greatly reduced. The voltage generated by the wind turbine should be boosted to reduce losses during the entire transmission process. Two methods are available to connect the wind turbine to the box transformer. One method connects the wind turbine to one transformer, and the other method connects multiple wind turbines to one transformer. Our design adopts one wind turbine connected to one transformer owing to its simple structure and convenient operation. When a wind turbine or transformer fails, the operation of the other units is not affected.

The influencing factors of LVRT are analyzed using a single wind turbine. The main issue is the damage to equipment caused by overvoltage and overcurrent, which results in grid isolation\[10\]. When the LVRT of a wind farm with multiple wind turbines is considered as a whole, the collection line becomes a major influencing factor. Because the collection-line impedance absorbs reactive power, which may result in insufficient reactive power at the collection point in the wind-farm booster station, reduction in the LVRT ability may occur. Because domestic and foreign researchers have conducted in-depth research on the LVRT technology of a single wind turbine, the technology is relatively complete. However, studies at home and abroad about the influence of a wind-farm collector-circuit layout on the LVRT characteristics are few. In addition, with regard to the layout design of a wind-farm line, the wind turbine is connected in series and parallel according to the distribution of the wind-turbine positions and types of collector lines. No research has been conducted on the optimization of the structure of the wind-farm collection line that considers economy and LVRT capability.

To study the relationship between the wind-farm collection line and LVRT characteristics, this work establishes the equivalent mathematical model of a wind farm according to its actual construction conditions, including the wind-turbine connection mode, wind-turbine layout, and wire types. It is concluded that the smaller the equivalent impedance of the wind-farm line structure is, the greater is the reactive power at the collection point in the wind farm, which is more helpful for grid-voltage recovery. According to this mathematical model, this study mainly investigates the optimization of the layout of the collection line under a grid-voltage symmetrical fault to realize minimum impedance and optimize the economic factor. The Monte Carlo method\[11-12\] is used to calculate the optimal line grouping, and the optimization method of the wind-farm collection-line structure that considers the economy and LVRT capability is obtained, which has certain practical significance.

2 Wind-turbine LVRT requirements

China has experienced a large number of large-scale wind turbine out-of-network accidents since 2008, which seriously affected the power system. According to the analysis of the causes of these accidents, the relevant off-grid specifications are formulated (the wind turbines have LVRT capability). In the event of system failure, the wind turbine is guaranteed to not be disconnected from the grid within a specified voltage range. Further, under certain circumstances, it can generate reactive power to help restore the grid voltage. The specific LVRT technical requirements are the following. (1) When the system fails, the voltage at the grid connection point of the wind farm drops to 0.2 p.u. The unit in the wind farm should be able to operate without being isolated from the grid for 625 ms. (2) When the grid voltage returns to 0.9 p.u. within 2 s after dropping, the wind turbines in the wind farm should ensure continuous operation without being isolated from the grid. The wind-farm LVRT requirements are shown in Fig. 1\[13-14\].

With the continuous improvement in the wind-turbine LVRT technology, most wind turbines have dynamic reactive-power support capability and can provide reactive power. However, because of the different control strategies, supports for reactive current also differ. The stand-alone model of a wind turbine is shown in Fig. 2.
According to the analysis of the stand-alone model of a wind turbine and the requirements for network specification, the magnitude of the dynamic reactive current generated by the wind turbine is determined using the terminal voltage of the wind turbine\(^{[13]}\), as expressed by Eq. (1).

\[
I_{\text{tur}} \geq 1.5(0.9 - U_{\text{tur}})
\]  

\(U_{\text{tur}}\) is the per unit value of the terminal voltage of a stand-alone generator.

### 3 Structural composition of a single wind turbine system and wind farm

The structure of the permanent-magnet direct-drive WPGS includes a wind turbine, a permanent-magnet synchronous generator, a machine-side converter, a grid-side converter, and the related control system, as shown in Fig. 3. To satisfy the LVRT requirement of a single wind turbine, a crowbar circuit is added to the DC side of the wind turbine to consume excess energy when a short-circuit fault occurs, maintaining the stability of the DC bus voltage.

The permanent-magnet direct-drive wind turbine adopts a back-to-back dual-PWM full-power converter connected to the grid. The control system of the machine-side converter is a rotor flux-oriented vector system to achieve maximum power tracking of the wind turbine and ensure that the power factor of the generator is 1.0. The control system of the grid-side converter is the grid-voltage-orientation vector control system, which is used to stabilize the DC-side capacitor voltage and provide a certain amount of reactive power to help restore the grid voltage\(^{[15]}\).

Most onshore wind farms adopt AC transmission systems in which the voltage is first rectified, boosted, and transmitted. The present study considers a wind farm with a capacity of 24 MW as an example and assumes that the field is plain. The booster station is equipped with STATCOM. The wind-energy data in the field is collected by the wind tower to analyze the wind direction and wind energy. We assume that the main wind and main wind energy directions in this field are both in the east direction and the distributions of the wind direction and wind energy are basically the same. Under the condition of the distribution of wind-energy resources, the layouts of the wind turbine locations are limited to optimize the lines. The wind farm topology is shown in Fig. 4, which contains 12 permanent-magnet direct-drive wind turbines with a capacity of 2 MW. The distance between each wind turbine is 1 km. The closest distance of the wind turbine in each group to the booster station is 2 km. By considering the capacity of the wind farm, economy, and applicability, the selected line layout type is overhead line LGJ-150/25\(^{[16]}\).
the wind-turbine position\textsuperscript{[17]}. The grouping of the wind turbines is evenly distributed according to the number of wind turbines and current-carrying capacity of the collection lines to prevent the collection lines from becoming very long due to excessive grouping. On the other hand, because the grouping is too small, we need to adopt a large-section collection line to meet the current-carrying capacity and increase the economic aspect. This series of design basis are considered from the economic aspect of a wind farm and have not been analyzed in terms of the requirements of LVRT of wind farms, making the integration of wind farms into the grid more stable. Therefore, this study considers the line structure of the wind farms from the perspective of LVRT characteristics and economy, which provides relevant applications.

4 Influence of collection line impedance on LVRT

The wind-farm modeling in this study is based on a single wind turbine. The electric energy is transmitted from the collection line after the first step of boosting the electric energy generated by the wind turbine. Then, the voltage is introduced into the grid after the second boosting by the transformer after the multiple sets of lines become equivalent to a single line. Throughout the wind-farm modeling process, the single wind-turbine model can utilize the existing modeling techniques. The wind-turbine model derives the basic characteristics of the wind turbine using the Betz theory. The permanent-magnet direct-drive generator model uses coordinate transformation to simplify the mathematical model. The machine- and grid-side converter models are verified by analyzing the topological structure and performing coordinate transformation\textsuperscript{[18]}. The equivalent power of the entire wind farm consists of the sum of the power of each wind turbine. In addition to the equivalence of the current-collection line, this study considers a small wind farm as an example and ensures that the collection line adopts the same model. Thus, calculation of the impedance of the collection line is simplified\textsuperscript{[19]}.

As shown in Fig. 4, we calculate series wind-turbine collection-line impedance $Z_i$ and total collection-line impedance $Z$.

\begin{equation}
Z_i = z_{i1} + z_{i2} + \cdots + z_n
\end{equation}

\begin{equation}
Z = \frac{1}{z_1} + \frac{1}{z_2} + \cdots + \frac{1}{z_n}
\end{equation}

When the line unit impedance value is constant, the line impedance of the wind-farm is proportional to the length, and the longer the length is, the greater the impedance is.

The wind farm is composed of a single wind turbine. Therefore, the dynamic reactive current of the wind farm is mainly generated by the wind turbine during fault and transmitted to the interconnection point of the wind-farm collection line at a certain distance. According to the requirements of GB/T 19963-2011, when a symmetrical grid fault occurs at the interconnection point of a wind farm and the voltage is 20%-90% of the nominal voltage, Eq. (4) needs to be satisfied.

\begin{equation}
I_0 \geq 1.5(0.9 - U_0)
\end{equation}

Here, $U_0$ is the per unit value of the voltage at the interconnection point of the wind-farm collection line circuit.

Because of the influence of the impedance of the collection line in the wind-farm, a voltage loss occurs, and the relationship between $U_{tur}$ and $U_0$ is expressed in Eqs. (5) and (6).

\begin{equation}
U_0 = U_{tur} - \frac{P_{tur} R_{tur} + Q_{tur} X_{tur}}{U_{tur}}
\end{equation}

\begin{equation}
U_0 = U_{tur} - \Delta U
\end{equation}

From the analysis of Eqs. (4) and (6), we can observe that the reactive current required to satisfy the collection point in the collection line is larger than that of the wind-turbine terminal, and a reactive-power loss is generated in the transmission line and transformer. The line loss is dominant. Therefore, the reactive power generated by the wind turbine cannot satisfy the LVRT requirements of the wind farm. In this case, we need to provide an additional reactive-power compensation device at the booster station to provide the reactive power. According to Ref. [20], reactive power $\Delta Q$ provided by static var generator (SVG) under a symmetric fault with voltage drop of 0.2 p.u. is obtained, which is the per unit value calculated using Eq. (8). It is composed of reactive power $\Delta Q_1$, \ldots, $\Delta Q_n$.
which compensates the line loss, and reactive power \( \Delta Q_2 \) provided by SVG when the reactive power loss in the fault is ignored. When the voltage drops are the same, \( \Delta Q_2 \) does not change.

\[
\Delta Q_2 = \frac{P^2 + Q^2}{U_{tu}^2} (R_i + jX_i) \quad (7)
\]

\[
\Delta Q = \Delta Q_1 + \Delta Q_2 = 7.5P_{tu} R_i + 1.575X_i \quad (8)
\]

\[
Q_0 = Q_{tur} - \Delta Q \quad (9)
\]

\( Q_0 \) is the reactive power provided by the wind turbine at fault, and \( Q_{tur} \) is the equivalent reactive power at the wind-turbine terminal. From Eqs. (8) and (9), we can conclude that \( \Delta Q_2 \) does not change when the active power of the wind turbine is constant. The smaller \( \Delta Q_1 \) is, the smaller is the reactive power provided by SVG. Because \( Q_{tur} \) does not change, the smaller \( \Delta Q \) is, the larger is \( Q_0 \), i.e., the smaller the impedance value of the collection line is, the smaller the reactive power loss of the line is and the larger is the reactive power provided by the wind turbine at the fault point.

5 Optimization model of a wind farm collection line structure

According to the theoretical analysis, when the impedance of the current-collection line is smaller, the reactive power provided at the point where the wind turbine is displaced at the fault point is larger, which contributes to the voltage recovery at the collection point. To reduce the value of \( \Delta Q \) and better achieve LVRT, a method to reduce the line reactive loss can be employed. We should ensure that the line impedance of the collector system is as small as possible. The wind turbines in wind farms are generally divided into multiple groups, and the wind turbines are then connected in series and then in parallel. From the series-parallel impedance properties, we learn that as the number of wind-farm line groups increase, the equivalent impedance of the wind farm becomes smaller. However, the more groups are there in the wind farm, the longer is the collection line, which is not consistent with the economic requirements. Therefore, combining the minimum line impedance with the economy of the collection line is necessary to design a set of optimized and reasonable wind-turbine distributions.

According to the analysis of an actual situation, the economic factors of the line are prioritized. The proportion is slightly higher than the ratio of the impedance value. Therefore, the weighting coefficient of the impedance value is 0.4, and the weighting coefficient of the line economic loss is 0.6. \( x \) represents the number of sets of wind farm collection lines, and a mathematical model is established according to the wind farm.

**Economic loss** \( f(x) \) is expressed as

\[
f(x) = a(2x + 12 - x) = ax + 12a = 30x + 360 \quad (10)
\]

Line impedance \( Z \) is expressed as

\[
Z = \frac{1}{z_1} + \frac{1}{z_2} + \cdots + \frac{1}{z_m} = \frac{b}{\prod_{m=1}^{x} (i_m + 1)} \prod_{m=1}^{x} (i_{m+1}) \quad (11)
\]

Normalized column weighted objective function \( y_{\min} \) is expressed as

\[
y_{\min} = 0.6 \left( \frac{f(x)}{f(2)} \right)^2 + 0.4 \left( \frac{Z}{Z_{2(6,6)}} \right)^2 \quad (12)
\]

In Eqs. (11) and (12), \( a \) is 300,000 RMB per km, which is the unit price of the collection line. \( b \) is the unit impedance value of overhead line LGJ-150/25. \( i_m \) is the number of wind turbines in the \( m \)th group line. \( f(2) \) represents the economic loss of the collector line when the wind-farm wind turbine is divided into two groups. \( Z_{2(6,6)} \) is the number of wind turbines in each group when the wind farm is divided into two groups.

The constraints of the wind farm on the objective function are expressed as follows.

\[
\begin{align*}
12 & < x \leq 12 \\
8 & < i_m \leq 8 \\
\sum_{m}^{x} i_m & = 12 \\
1 & \leq m \leq x \\
x_i, i_m & \in N
\end{align*}
\]

According to the condition of minimum impedance and excellent economy, this study establishes an optimized model of a wind-farm line.
structure, which can accurately calculate the weighting values of the different line structures under two conditions. After the comparison, an optimal structure is obtained for reference.

6 Simulation and analysis

Because the unit impedances of the collection line are equal, the effect of simplifying the simulation model can be achieved by changing the distance of the transmission line from the equivalent unit of the wind farm to the booster station. When the low-voltage side of the booster station experiences a three-phase symmetrical voltage-drop fault at 1 s, the voltage-drop value is 0.2 p.u., the fault duration is 0.625 s, and we set different the wind-farm equivalent line lengths (50 and 200 m respectively). The influence of the line-impedance value on the LVRT is analyzed according to the reactive-power waveform of the collector in the collection line. The waveforms of the three-phase AC phase voltage and the effective value of the phase-A line voltage are shown in Figs. 5 and 6, respectively. Fig. 5 shows that the three-phase AC power drops from 1 s, and recovers from the fault at 1.625 s. Fig. 6 shows that the voltage drops by 20%.

When a three-phase symmetrical grid fault occurs, the speed of the generator and the capacitor voltage at the DC side increase. Using the vector system oriented by the rotor flux linkage, a speed reference value is provided to control the change in the generator speed. The speed reference value and actual speed waveform are shown in Fig. 7, which shows that the generator speed is synchronized with the speed reference value at 0.5 s. When a voltage symmetrical fault occurs, the generator torque ripple is not large and remains stable. Using a grid-voltage vector control and a crowbar circuit, the DC voltage reference value is obtained to realize DC-side voltage tracking. In addition, by limiting the upper and lower limits of the crowbar-circuit voltage value, the magnitude of the DC voltage after the fault is stabilized. The DC voltage reference value and actual DC voltage waveform are shown in Fig. 8. The waveforms of grid-side currents \(i_d\) and \(i_q\) are shown in Figs. 9 and 10, respectively. Fig. 8 shows that the DC-side voltage before the fault is stable at around the rated value. However, the voltage increases after the fault, and the voltage is stabilized to approximately 20% to 25% of the reference value by the action of the crowbar circuit. Figs. 9 and 10 show that recovery of the grid voltage is ensured after a fault occurs. First, reactive power is provided. Grid-side reactive current \(i_q\) is not zero, and active current \(i_d\) becomes zero.
Analysis of Figs. 7-10 reveals that the wind-power system can track the generator speed and DC voltage under a symmetrical voltage-drop grid fault, stabilize the DC side voltage to prevent the capacitor from being broken down, and achieve LVRT. To study the influence of the collection line on the reactive power at the collection point of the wind farm, the waveforms under different line lengths are compared and analyzed. Fig. 11 shows the comparative simulation waveforms of the reactive power at line lengths of 0.5 km and 2 km.

The analysis of Fig. 11 indicates that the reactive power generated by the collection line at the 0.5-km collection point is more than that at the 2-km collection point. Therefore, the shorter the collection line is (i.e., the smaller the equivalent impedance of the wind-farm line is), the larger is the reactive power generated by the intersection of the wind-farm collection lines. According to the relationship between the reactive power and voltage, as expressed in Eq. (7), when the power generated by the wind farm and the line impedance are constant, the smaller the reactive loss is, the larger is the voltage amplitude. Therefore, when the grid voltage drops, reactive power is provided to the fault point, which compensates the inductive reactive power of the impedance loss; thus, the grid voltage can recover. Fig. 11 shows that the shorter the line is (i.e., the smaller the equivalent impedance of the wind-farm line is), the larger is the reactive power provided by the intersection of the wind-farm lines. In addition, when the reactive power is compensated at the fault point, the fault voltage can be restored to the normal operating range required by the grid-connection criterion to ensure that the wind farm quickly returns to its normal state and supplies power to the grid.

According to the objective function and constraints, the Monte Carlo method is used to write the MATLAB nonlinear integer-programming program to calculate the optimal grouping result of the wind farm. The algorithm flowchart is shown in Fig. 12.

First, we create the $m$ function, define the objective function, and write the objective function and constraints. Then, we set larger initial value $y_0$, assign random number $i_m$ according to the condition, and round up $i_m$. We calculate $y$ according to provided $i_m$, compare it with the set initial value, re-assign the smaller value to $y_0$, and perform cycle comparison to obtain the minimum. We modify the number of sets of collection lines, calculate minimum value $y$ in the different groups, and perform comparison to obtain an optimized grouping structure.
First, the weighting value of the number of different wind turbines in the same group situation is obtained by simple calculation, as listed in Tabs. 1-6.

### Tab. 1 Weighting value of the number of different wind turbines ($x = 2$)

| $i_m$ | $y$  |
|-------|------|
| (8, 4) | 0.9374 |
| (7, 5) | 0.9838 |
| (6, 6) | 1.0000 |

### Tab. 2 Weighting value of the number of different wind turbines ($x = 3$)

| $i_m$ | $y$  |
|-------|------|
| (8, 1, 3) | 0.7328 |
| (8, 2, 2) | 0.7428 |
| (7, 2, 3) | 0.7539 |
| (6, 3, 3) | 0.7678 |
| (5, 4, 3) | 0.7746 |
| (4, 4, 4) | 0.7795 |

### Tab. 3 Weighting value of the number of different wind turbines ($x = 4$)

| $i_m$ | $y$  |
|-------|------|
| (1, 8, 2, 1) | 0.7993 |
| (2, 7, 2, 1) | 0.8032 |
| (3, 6, 2, 1) | 0.8054 |
| (3, 5, 3, 1) | 0.8077 |
| (4, 5, 2, 1) | 0.8063 |
| (4, 3, 3, 2) | 0.8143 |
| (3, 3, 3, 3) | 0.8163 |

### Tab. 4 Weighting value of the number of different wind turbines ($x = 5$)

| $i_m$ | $y$  |
|-------|------|
| (1, 1, 1, 1, 8) | 0.8920 |
| (1, 1, 1, 2, 7) | 0.8932 |
| (1, 1, 2, 2, 6) | 0.8947 |
| (1, 1, 1, 3, 6) | 0.8938 |
| (1, 2, 2, 2, 5) | 0.8964 |
| (1, 2, 2, 3, 4) | 0.8972 |
| (2, 2, 2, 2, 4) | 0.8986 |
| (1, 2, 3, 3, 3) | 0.8977 |
| (1, 1, 1, 4, 5) | 0.8941 |
| (1, 1, 2, 3, 5) | 0.8954 |
| (2, 2, 3, 3, 3) | 0.8992 |
| (1, 1, 3, 3, 4) | 0.8960 |

Comparison of the data listed in Tabs. 1-6 illustrates that when $x = 3$ and the number of wind turbines in each group is $i_m = (8,1,3)$, the weighted minimum value of the objective function is $y_{\text{min}} = 0.7328$. The minimum values in the same-group case are when $x = 2, i_m = (8,4), y = 0.9374; x = 3, i_m = (8,1,3), y = 0.7328; x = 4, i_m = (1,8,2,1), y = 0.7993; x = 5, i_m = (8,1,1,1,1), y = 0.8920; x = 6, i_m = (1,1,1,1,1,7), y = 0.9966; and $x = 7, i_m = (1,1,1,1,1,1,6)$, $y = 1.1084$. The simulation results of the minimum weighted values of the different grouping structures obtained by the Monte Carlo method are listed in Tab. 7.

### Tab. 5 Weighting value of the number of different wind turbines ($x = 6$)

| $i_m$ | $y$  |
|-------|------|
| (1, 1, 1, 1, 1, 7) | 0.9966 |
| (1, 1, 1, 2, 6, 1) | 0.9972 |
| (1, 1, 2, 2, 5, 1) | 0.9978 |
| (1, 2, 2, 2, 4, 1) | 0.9986 |
| (2, 2, 2, 2, 3, 1) | 0.9994 |
| (2, 2, 2, 2, 2, 2) | 1.0000 |
| (1, 1, 1, 3, 5, 1) | 0.9974 |
| (1, 1, 1, 4, 4, 1) | 0.9975 |
| (1, 1, 2, 3, 4, 1) | 0.9981 |
| (1, 1, 3, 3, 3, 1) | 0.9983 |

### Tab. 6 Weighting value of the number of different wind turbines ($x = 7$)

| $i_m$ | $y$  |
|-------|------|
| (1, 1, 1, 1, 1, 1, 6) | 1.1084 |
| (1, 1, 1, 3, 1, 1, 1) | 1.1092 |
| (1, 4, 3, 1, 1, 1) | 1.1089 |
| (2, 2, 2, 2, 2, 1, 1) | 1.1097 |
| (1, 4, 2, 2, 1, 1, 1) | 1.1091 |
| (1, 5, 1, 2, 1, 1, 1) | 1.1087 |
| (2, 2, 3, 2, 1, 1, 1) | 1.1094 |

### Tab. 7 Minimum weighting values of the different grouping structures

| $x$ | $i_m$ | $y$  |
|-----|-------|------|
| 2   | (8, 4) | 0.9374 |
| 3   | (8, 1, 3) | 0.7328 |
| 4   | (1, 8, 2, 1) | 0.7993 |
| 5   | (1, 1, 1, 1, 1) | 0.8920 |
| 6   | (1, 1, 1, 1, 1, 1) | 0.9966 |
| 7   | (1, 1, 1, 1, 1, 1, 6) | 1.1084 |

Analysis of the data listed in Tab. 7 shows that when $x = 3$ and the number of wind turbines in each group is $i_m = (8,1,3)$, the weighted minimum value of
the objective function is $y_{\min} = 0.7328$. Finally, the comparison between the simple calculation data and Monte Carlo method results shows that the optimal results obtained by the latter are consistent with those of the former.

According to the simulation and program operation results, when the voltage drop is consistent, the reactive-power waveforms can be compared. In the entire process of wind-power transmission, the longer the collection line is, the larger is the voltage loss, the more reactive power is compensated by SVG, and the smaller is the reactive power of the wind turbine at the fault point. The voltage drop and loss have been verified to be reduced by shortening the length of the collection line. By combining the impedance and the economic factor, the optimized structure of the line of the wind farm is calculated as three sets of collection lines, and the numbers of wind turbines in each group are eight, one, and three.

7 Conclusions

This work comprehensively considers the economics of wind-farm lines and reactive-power support under a grid fault to optimize the structure of the collection line in wind farms. First, the relationship between the line impedance and reactive power under a grid fault is analyzed. We conclude that the smaller the equivalent impedance of the collection line is, the smaller are the voltage and power losses and the greater is the utilization of the reactive power generated by the wind turbine for voltage recovery. Then, the Monte Carlo method in nonlinear integer programming is used to establish the optimal model of the line structure with minimum line impedance and optimized economic factor. Finally, the proposed method is verified using simulation and examples.

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