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A Hybrid Cable Connection Structure for Wind Farms with Reliability Consideration

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ABSTRACT The collector system in wind farm has a large number of cables. When one of the cable fails, the power generated by the wind turbine (WT) cannot be collected into the substation through the faulty cable. That would make the profits for the wind farm reduced. Therefore, it is necessary to find a more reliable cable structure, which can transfer power as much as possible even if the cable failure occurs. In this paper, a new cable connection method is proposed in two main steps to improve both the reliability of the cable connection and the economic. Two different wind farms with the same climatological information and high voltage substation location are investigated and compared in the case study. In the first step, the minimum spanning tree (MST) algorithm is adopted to connect all wind turbines (WTs) to the substation. The cables used in collector system are the 33-kV middle voltage alternating current (MVAC) cables. Then the power production generated by WTs is transmitted from substation to the high voltage substation via a 132-kV transmission cable. The initial cable connection layout is obtained in the first step and the total trenching length is optimized to be minimum. In addition, cable selection in each branch can be determined based on the cable current carrying capacity. In the second step, reliability assessment is implemented by analyzing the expected energy not supplied (EENS). Based on EENS, the evaluation index LPC_{rel} is obtained. This index takes both reliability and economy into account. Additional cables found by particle swarm optimization (PSO) algorithm are added to the initial cable connection layout. Finally, a cable layout called hybrid structure is formed. What is more, by adding additional cables, the LPC_{rel} is reduced by 1.5%. The simulation results clearly indicate that the proposed method is better when the cable failure is considered.

INDEX TERMS Wind farm, MST algorithm, reliability and economy, PSO algorithm, cable connection layout.

NOMENCLATURE

V_0 [m/s]	The input wind velocity of upstream WT
R_0 [m]	The length of WT's blade
$S_0\ [m^2]$	Area wept by the WT's blade
R_{ij}[m]	Generated wake radius by the WT at row i, column j.
A_p, B_p, C_p	The coefficient of cable cost model
C_i	The unit price of cable i
$S_{n,i}$	The rated apparent power i
$I_{i,rated}$	The rated current of cable i
$U_{i,rated}$	The rated voltage of cable i
$cost_i$	The cost of cable i
L_i	The length of cable i
Q_i	The number of cable in line i
$P_{loss,ij}$	The power losses in cable at row i, column j
$R_{loss,ij}$	The resistance of cable at row i, column j
$S_{R,ij}$	The cross sectional area of cable at row i, column j
$\rho_{R,ij}$	The coefficient of resistance
$S_{overlap,ij}$	Overlapped area generated by upstream WT to affected downstream WT
V_{ij} [m/s]	Wake velocity generated by the WT at row i, column j

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L_{ij} [m]	Distance from upstream WT to downstream WT
V_{nm}	Wind velocity at row n, column m
ρ	Air density
$C_{p,opt}$	Optimal value of power coefficient C_p under MPPT control strategy
β	Blade pitch angle
δ_{opt}	Tip speed ratio
v	Wind velocity
E_{tol}	Energy yields of wind farm in one year
TE	Total number of time interval for energy yield calculation
T_i	Duration of time interval
C_0	Initial cable investment

I. INTRODUCTION

With the depletion of fossil fuel, human beings are facing severe energy challenges in recent years. Besides, fossil fuel consumption emits large quantities of greenhouse gases and causes environmental pollution. In order to sustain energy supply and deal with global warming, the best approach is probably to develop more renewable energy. Among them, wind energy has attracted a wide attention due to its abundant resources and easy to capture. According to Global Wind Energy Council (GWEC)'s Report, a quarter of the world's electricity comes from renewable energy by 2035, and 25% of renewable energy is occupied by wind energy [1]. This shows that the development prospects of wind energy are very positive. In addition, distributed generation like wind farm can provide power to local loads better in some areas, such as isolated islands, compared with traditional power grids.

When the layout of the WTs has been determined, a reasonable cable connection in the wind farm should be considered carefully. The cable connection should be able to successfully collect electricity and reduce the cable cost as much as possible. In order to get a better cable connection layout, various topologies are compared in [2] and power system is optimized in terms of the levelised production cost (LPC) and reliability. The value of LPC is related to initial investment in wind farms and the final energy yields. Therefore, a reasonable cable connection layout should be found to minimize initial cable investment and reduce the power losses. Some studies are done in [3]–[10] to optimize the cable layout. When the scale of wind farm is large, it is too difficult to get the final cable layout by directly analyzing and calculating. A clustering method is proposed in [3] to reduce the computational difficulties of the problem and can find the internal connection easily. However, in the process of clustering, the global optimal solution may be excluded. The total trenching length is considered in [4], [5] that all WTs is connected to the substation by applying a minimum spanning tree (MST) algorithm. Genetic algorithm (GA) is also widely used to obtain cable connections in [6]–[8]. A series of objective functions are proposed in [6] to optimize the value of the total cable length, power loss and cable cost. The final cable connection is found to minimize these factors. Reference [7] solves the problem of cable connection when there are more than one substation in the wind farm and the traveling salesmen problem (TSP) is applied as the cable connection algorithm. An integer-based GA is presented in [8] to find the optimal electrical configuration for power collector system. The cable size in each branch and the connection layout can be found but the cost for transmission cable is not taken into consideration. Compared with MST algorithm, GA algorithm takes longer time on calculation and the crossover cable may appear in the obtained cable layout. Particle swarm optimization (PSO) and other evolution algorithm are also applied in [9] and [10] respectively to optimize the interconnection. For the power collector system, it is necessary to minimize the occurrence of faults in the operation cycle of wind farm as much as possible. References [11]–[16] take the reliability together with economy into consideration. A novel transmission network reinforcement model considering cost-reliability is presented in [11]. In addition, the emission reduction and fuel saving are also taken as evaluation factors to improve the system reliability. In [12] and [13], the substation location and inner grid layout is determined together by analyzing EENS and the economic issues. The double-sided structure of the collector system is presented in [14] and this structure is more suitable for large offshore wind farms. Besides, it has strong applicability because this method can add additional cables to the original cable structure. In [15], the reliability of four common cable connection topologies is analyzed. In addition, it proposes a section enumeration technique to calculate the reliability in wind farms. Reference [16] puts forward a novel algorithm based on a sweep algorithm, and simulation results show that the algorithm can avoid cable crossings. Moreover, the multi-loop structures in [16] can save the cost when cable failure occurs. However, the initial cable cost of the multi-loop structures is too high because this structure introduced too much additional cables and switches.

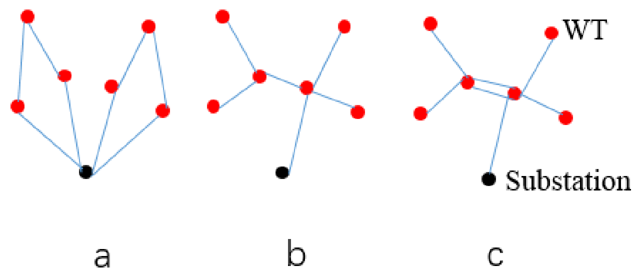

FIGURE 1. Three cable connection structure to be used in wind farm.

The cable connection structures proposed in the above literature can be divided into two types as shown in FIGURE 1(a) and FIGURE 1(b). Black dot indicates substation, while red dots indicate WTs. The structure in FIGURE 1(b) is a radial topological structure. In this structure, a certain number of WTs are connected in series. The number of WTs in each series is determined by the rated current carrying capacity of cables. The radial topological structure is widely used because of its low investment cost. However, if a cable failure occurs somewhere, the WTs behind it will not work properly. So the reliability of the structure in FIGURE 1(b) is unsatisfactory. The high-reliability topological structure of the collector system, the double-sided ring structure shown in FIGURE 1 (a), is to connect a certain number of WTs through the cable to form a ring. When only one cable fails, the remaining topology can still connect all WTs to the grid through other normally operating cables. Compared with the radial structure, the ring structure greatly improves the reliability of the system. However, the number of large cross-section cables is relatively large, and the cable cost increases accordingly. With the consideration of the contradiction between the radial topology and the ring topology in term of economy and reliability, a hybrid structure of the collector system is given, in which the economy and reliability are between another two mechanisms, as shown in FIGURE 1(c). In a wind farm, the radical topological structure can significantly reduce the capital cable cost. So the WTs are connected by this structure. In order to make up for the lack of reliability, additional cables should be added to the radical structure. The PSO algorithm is applied in this paper to find these additional cables.

The remaining parts of the paper is composed as follows. Section II introduces Jason wake model, cost model and energy yield model. Section III presents the evaluation index— levelised production cost (LPC), and the initial cable connection way—MST. Also, the proposed index $\boldsymbol{LPC_{rel}}$ based on both reliability and economy is descripted. And the PSO algorithm is employed to find the additional cable. Then the whole optimization framework are introduced subsequently. Simulations are carried out in Section IV and conclusions are drawn in Section V.

II. WIND FARM MODELS

The Jason wake model is introduced in this section. Then the calculation method of the cable cost is explained. Finally, the calculations of power losses and energy yields are given.

A. JASON WAKE MODEL

When the wind passes through a wind farm, the wind speeds will be changed by the different positions of the WT. Generally speaking, the wind speed will gradually decrease as the number of WTs being passed increases. This phenomenon is called wake deficit in [17]. Jason wake model is chosen in this paper to calculate the wind speed in different positions, as this model is convenient in calculating wind speed with less prediction error [18]. The mathematical expression is as follows [19], [20].

$$V_{ij} = V_0 - V_0\left(1-\sqrt{1-C_t}\right)\left(\frac{R_0}{R_{ij}}\right)^2\left(\frac{S_{overlap,ij}}{S_0}\right) \quad (1)$$

$$R_{ij} = R_0 + kL_{ij} \quad (2)$$

Sometimes a downstream WT is affected by multiple upstream WTs. To calculate the influence of these upstream WTs, [21] proposed a method. The wind speed of WT at row n, column m can be calculated as

$$V_{nm} = V_0\left[1-\sqrt{\sum_{i=1}^{N\_row}\sum_{j=1}^{N\_col}\left[1-\left(\frac{V_{ij}}{V_0}\right)\right]^2}\right] \quad (3)$$

B. COST MODEL

The introduced cost model in wind farm is based on the cables' rated power. The specific mathematical expression is as follows [22]

$$C_i = A_p + B_p exp\left(\frac{C_p S_{n,i}}{10^8}\right)^2 \quad (4)$$

$$S_{n,i} = \sqrt{3} I_{i,rated} U_{i,rated} \quad (5)$$

To satisfy the cable current carrying capacity, there may more than one cable needed between this branch. So the cost should be calculated as

$$cost_i = Q_i C_i(x, y) L_i(x, y) \quad (6)$$

where Q_i indicates the number of cable in line i. Then the total cable cost in line i can be calculated by using the formula (6).

C. ENERGY YIELDS MODEL

The energy yields are related to three aspects: power production, power losses and operating period of wind farm. The specific calculation formula and analysis are as follows.

1) POWER PRODUCTION

The formula can be used to calculate the power production generated by the WT [23], [24].

$$P_{m,ij} = 0.5\rho C_{p,opt}\left(\beta, \delta_{opt}\right)\pi R_0^2 v^3/10^6 \quad (7)$$

In the simulations, the power production of each WT is determined by assuming a maximum power point tracking strategy [25] applied on the turbine. Thus the total power generated by WT is calculated as follows

$$P_{tol} = \sum_{j=1}^{N\_col}\sum_{i=1}^{N\_row} P_{m,ij} \quad (8)$$

2) POWER LOSSES IN CABLES

The power losses along the cables can be calculated as

$$P_{loss,ij} = 3I_{ij}^2 R_{e,ij} \quad (9)$$

$$R_{e,ij} = \rho_{R,ij}\frac{l_{R,ij}}{S_{R,ij}} \quad (10)$$

The length of cable depends on the distance of WTs. The total power losses is shown as

$$P_{loss,tol} = \sum_{i=1}^{N\_row}\sum_{j=i}^{N\_col} P_{loss,ij} \quad (11)$$

Combining formulas (7) to (11), the energy yields can be expressed as

$$E_{tol} = \sum_{i=1}^{TE}\left(P_{tol,i} - P_{loss,tol,i}\right) T_i \quad (12)$$

III. PROBLEM FORMULATION FOR OPTIMIZATION

The LPC which selected as the evaluation index is introduced firstly. Then a cable connection method MST algorithm is introduced to form a radical topological structure. After the cable layout is obtained, it is analyzed by reliability metrics. The calculation formula for EENS is introduced and an other new evaluation index LPC_{rel} is given. Finally, the cable layout is further optimized on the basis of reliability and economy by adding cables. It should be noted that PSO algorithm is used to find these additional cables.

A. LEVELISED PRODUCTION COST

LPC is the ratio between initial investment and energy yields. In addition, the wind farm life cycle and bank interest rate are also considered in LPC. The lower the LPC value, the lower the cost of energy yields. The specific calculation of LPC is as follows [26]

$$\mathrm{LPC} = \frac{C_0 r\,(1+r)^{N_y}}{(1+r)^{N_y}-1}\frac{1}{E_{tol}} \tag{13}$$

$$C_0 = \sum_{t=1}^{N_y}\sum_{i=1}^{N} cost_i\,(1+r)^{-t} \tag{14}$$

B. MINIMUM SPANNING TREE (MST)

In a wind farm, if the locations of the WTs are regarded as nodes and the cables between WTs are regarded as branches in a graph, then the cable connection problem can be transformed into a MST problem in the traditional graph theory. The relative algorithm can be expressed as [27]

$$G_T = (V, B_T, W_T) \quad G_T \le \mathrm{G},\ B_T \le B,\ W_T \le W \tag{15}$$

where G is the undirected weighted graph, G_T is a subgraph representing MST. B_T is the total branches in G_T. W_T is the total branch weights in G_T. In this paper, LPC is used to represent the branch weight. V represents the number of all the nodes. In other words, V is equal to the sum of the number of substation and WTs. The LPC value of the MST can be given as follows.

Objective

$$\min\left\{LPC^{G_T}(x,y)\right\} = \min\left\{\left[\frac{C_0^{G_T}(x,y)\,r\,(1+r)^{N_y}}{(1+r)^{N_y}-1}\right]\frac{1}{E_{tol}^{G_T}(x,y)}\right\} \tag{16}$$

Constraints

$$I_i \le I_{i,rated}; \quad i \in [1, N_G] \tag{17}$$

$$\mathrm{x} \in [0, L_x]; \quad y \in \left[0, L_y\right] \tag{18}$$

where L_x and L_y represent the predefined area as shown in FIGURE 5. The positions of substation and WTs must be strictly controlled in this predefined area.

To solve MST problem, prim method and kruskal method are the general methods to be widely used [28]. Prim algorithm is chosen in this paper and the process is shown below.

1) Selecting the search starting point N. Initially the substation location is set as the search starting point N.
2) Creating two sets, A and B. The remaining nodes are put in set A. In other words, set A contains the nodes that have not visited by the algorithm.
3) Comparing the weight of all the branches that connected to N and Selecting the branch with minimum weight as the branch of spanning tree. The other node which is connected to the selected branch is chosen as the starting point N for the next phase. And the node will move from set A to set B.
4) According to the cable current carrying capacity, the suitable cable can be chosen in each branch and recorded subsequently.
5) The program will not terminate until set A becomes empty, otherwise turn into step 3).

C. RELIABILITY ASSESSMENT OF WIND FARM

The random failure, which occurs in middle voltage alternating current cables, is considered in this paper. The other failures, such as WT fault, are ignored. In this paper, EENS is regarded as a reliability index and is expressed as follows [29].

$$\mathrm{EENS} = \mathrm{T}\cdot P_n \tag{19}$$

$$\mathrm{T} = \mathrm{MTTR}\cdot\tau \tag{20}$$

where P_n represents the average power of the n$^{\mathrm{th}}$ WT in a year. The recommended value of MTTR for MDAC cable is 1440 h/occ. The recommended value of failure rate τ is 0.015 occ/year/km [13].

The formula of LPC indicates the relationship between the energy yields and the initial investment. However, the energy yields calculated by formula (12) contains the EENS. If the reliability of wind farms is considered, the LPC calculation method should be as follows

$$LPC_{rel} = \frac{C_{new} r\,(1+r)^{N_y}}{(1+r)^{N_y}-1}\frac{1}{E_{rel}} \tag{21}$$

$$E_{rel} = E_{tol} - EENS \tag{22}$$

$$C_{new} = C_0 + C_{add} \tag{23}$$

where E_{rel} is the remaining energy yields after subtracting the EENS and C_{add} presents the cost of additional cable. The value of LPC_{rel} is taken into consideration for both economy and reliability.

D. USING PSO TO FIND ADDITIONAL CABLES

As stated in the introduction, in order to optimize both economy and reliability, a hybrid cable structure is more reasonable. That means additional cables should be connected to the radial topological structure (in this paper is MST) to make the LPC_{rel} smaller. The PSO algorithm, proposed by Eberhart and Kennedy in 1995, has been extensively applied due to its fast convergence speed and easy implementation. In this paper, PSO algorithm is used to further optimize the cable connection layout and reduce LPC_{rel}.

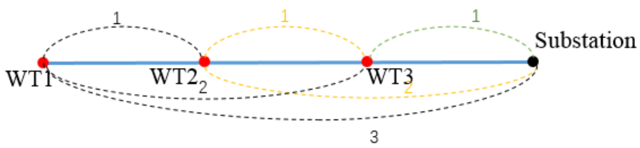

FIGURE 2. A branch of MST.

There is a branch of the spanning tree as shown in FIGURE 2. Black dot represents substation and red dots represent WTs. Blue lines are cables between WTs. The process of using the PSO algorithm to find additional cables is shown below. The total number of particles in the PSO algorithm is equal to the number of WTs. The WT1 in FIGURE 2 represented by particle x_1 in the PSO algorithm. The WT1 has three additional cables that may be added into this branch and is represented by black dashed line in FIGURE 2. So set a 3-bit binary number for the WT1. WT1 is set as a 3-bit binary number. So it ranges from 0 to 7. 0 denotes that the corresponding path is not selected, and 1 denotes that the path is selected. In the same way, set a 2-bit binary number and a 1-bit binary number for WT2 and WT3 respectively. The particle x_2 and x_3 represents WT2 and WT3 respectively in the PSO algorithm. Then these three particles are put into the PSO algorithm and the final best values of particle x_1, x_2 and x_3 are 5, 1 and 1 respectively. Then x_1 is converted to a 3-bit binary number [101], x_2 is converted to a 2-bit binary number [01] and x_3 is converted to a 1-bit binary number [1]. That means path 3 and path 1 for the WT1 are selected for the added cables. As for the other two WTs, the path 1 is chosen respectively.

The general idea is to use LPC_{rel} as fitness function to update the value of each particle. Then the binary number is obtained by decoding the corresponding values of each particle. The additional cables may be found. The reliability and the economy of final cable layout are improved. The relative optimization steps of using PSO to find additional cables are as follows

1) Initialize particle population. The size of the total particle swarm equals the number of WTs.
2) Evaluate the fitness of each particle, the position and fitness of each particle are stored in the p-best (Q_i^b) of each particle, and the location and fitness of the best individual in all p-bests are stored in g-best (Q_g^b).
3) Update the velocity and position of particles. Q_i^k is the value of particle after the k th iteration. Q_i^{k-1} is the value of particle after the k-1 th iteration. V_i^k is the velocity of particle in k th iteration. ω_k is the inertia weight. c_1 and c_2 are learning factors. r_1 and r_2 are random number.

$$V_i^k = \omega_k V_i^{i-1} + c_1 r_1 \left(Q_i^b - Q_i^{k-1}\right) + c_2 r_2 \left(Q_g^b - Q_i^{k-1}\right)$$
$$Q_i^k = Q_i^{k-1} + V_i^k$$

4) Compare each particle with its previous optimal position, in case of a better position, it is selected as the current position.

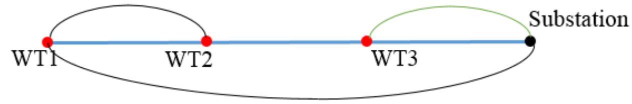

FIGURE 3. A branch of MST optimized by PSO.

5) Compare all current p-bests with g-best of the previous iteration cycle and update g-best.
6) When the termination condition is satisfied, the result is output; otherwise, the program will go back to step 2).

The branches of MST shown in FIGURE 2 are optimized through the above process. If the optimized values of x_1, x_2 and x_3 are 5, 0 and 1, respectively. Then the corresponding binary number is [1 0 1], [0 0] and [1]. The final cable layout after adding cables is shown in FIGURE 3. The final selected cables are represented by solid lines. For this branch, the optimal case is that WT1 and WT3 need to add cables while WT2 does not need to add cables.

E. CABLE CONNECTION LAYOUT OPTIMIZATION FRAMEWORK

The location of substation is closely related to the cable connection layout in the wind farm. Therefore, a reasonable cable connection layout should be determined together with the substation location. Initially, the substation location is used as the search starting point and the corresponding connection layout can be obtained. After getting the preliminary connection layout, the PSO algorithm is used to optimize the layout. Ultimately, the reliability of collector system is improved and the value of LPC_{rel} is reduced. The whole optimization framework is shown in FIGURE 4.

In [30], various cable data can be found and used as a cable database. XLPE-Cu AC cables are chosen in this paper. Some 33 kV MVAC cables are used for the collector system and one 132 kV HVAC cable is used for the transmission system.

The relevant climatological information comes from the work of the Norwegian Meteorological Institute [31]. The data records have the wind speed and direction in a region during a year.

Before the simulation, it is assumed that the WTs' layout is determined and will not change. So the power generated by each WT can be calculated according to the climatological information. Then the optimal substation location and corresponding cable connection should be determined together by using MST algorithm. In this step, the substation location is supposed to be found in a predefined area (18). Every time a new substation location is added to MST algorithm, the substation location is set as the initial search starting point N. A node is selected in set A which has the minimum LPC added into MST. The branch between search starting point and the selected node should be recorded. The node just selected is moved from set A to set B. In addition, the node just selected is set as the search starting point N to find the next node. The MST function will not be ended until set A is empty. When the MST function is finished, the cable connection layout corresponding to a substation location is obtained.

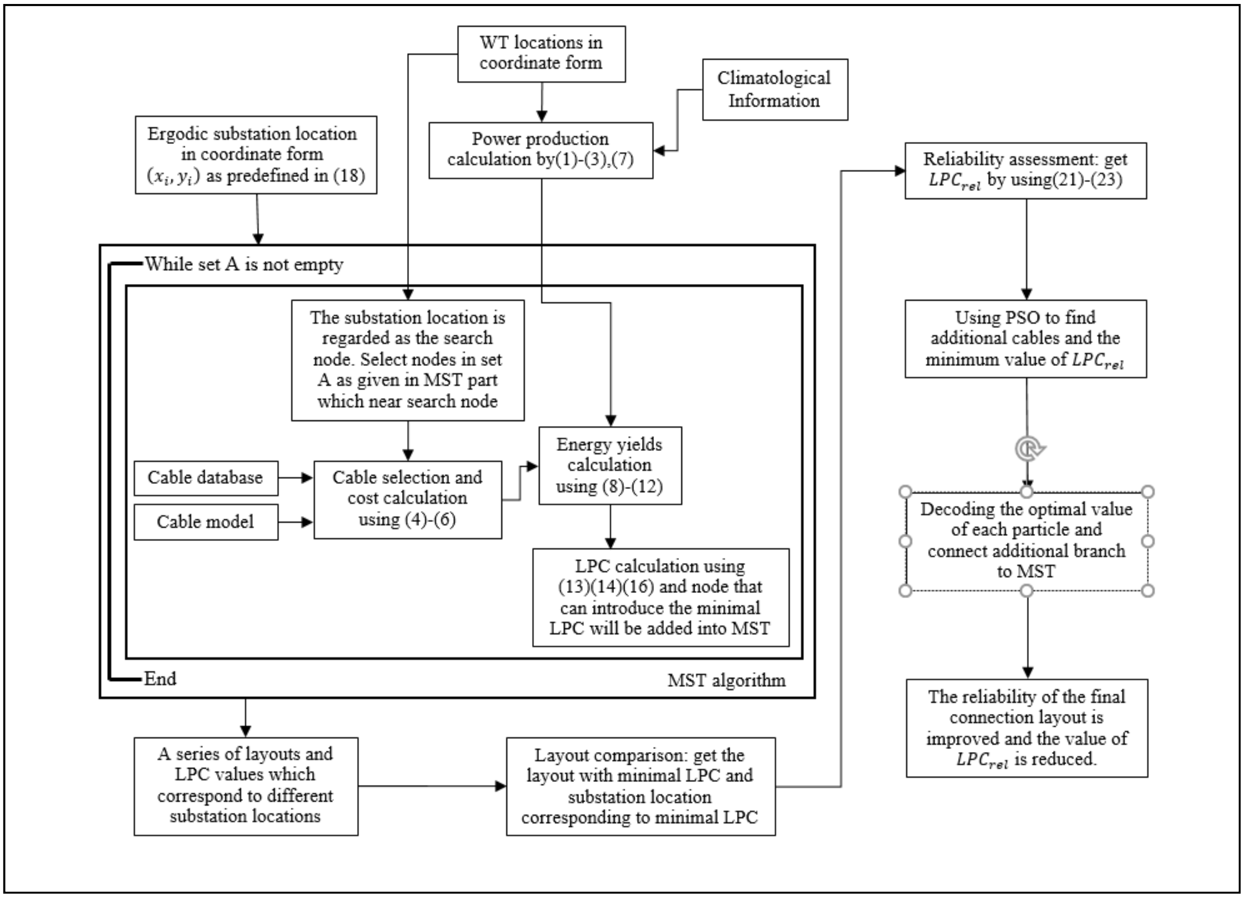

FIGURE 4. Optimization framework for the wind farm.

After all substation location is attempted, the best layout with minimum LPC and substation location can be found. In the next step, the value of EENS is taken to evaluate the reliability of cable connection layout. Thus the index LPC_{rel} can be obtained by formula (21) (22) (23). LPC_{rel} has a better performance in reliability and economy. The PSO algorithm, which is able to solve the nonlinear optimization problem, is applied to minimize the fitness value LPC_{rel}. Then the additional cables can be found by deducing the optimal value of each particle. Finally, these additional cables are added into MST to form a hybrid structure.

IV. CASE STUDIES

The simulation is carried out on the MATLAB platform. The proposed hybrid structure is executed for two different wind farms, a regular wind farm and an irregular wind farm. These two wind farms have 24 and 18 WTs respectively. The WT type used in the wind farm is Vestas V90-2.0 MW [32] (90 m rotor diameter).

In FIGURE 5, the black square represents the wind farm, where Lx represents the width of the wind farm, and Ly represents the length of the wind farm. All positions of WTs in the wind farm are expressed in a coordinate form. Firstly, the WTs are connected to substation in the wind farm. Then the power is transmitted to the high voltage substation

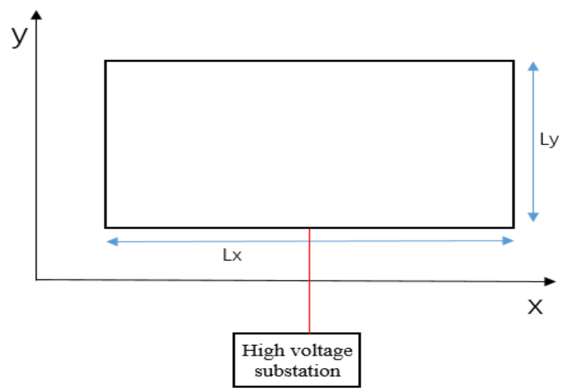

FIGURE 5. Basic description of a wind farm.

TABLE 1. Detail color for cable.

Voltage level	33 kV			
Type	AC			
Color	Yellow	Magenta	Blue	Red
Cable sectional area, mm^2	70	120	150	300

through transmission cable which is represented by a red line. In addition, the colors for cable used in the study case is shown in table 1.

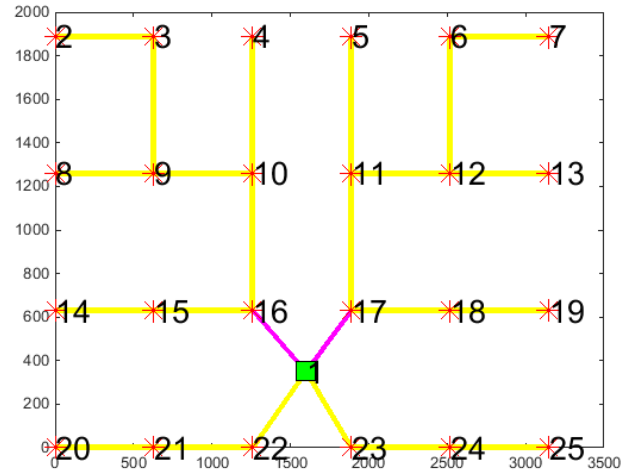

FIGURE 6. The initial cable connection in regular wind farm.

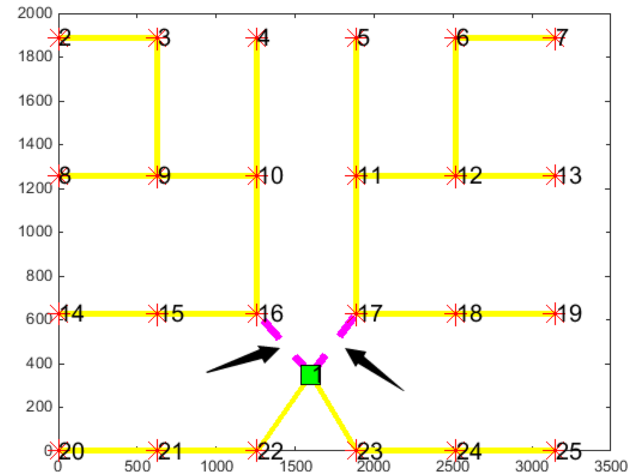

FIGURE 7. The final cable connection by adding cables in regular wind farm.

In the first step, the WTs in the wind farm are connected to the substation by using the MST algorithm. The best substation location is determined together with cable connections. Considering the cable current carrying capacity, the cable in each branch should be chosen easily. Then reliability analysis of the initial cable layout is carried out. By analyzing EENS, LPC is updated to LPC_{rel}. Without changing the original cable selection, the value of LPC_{rel} is reduced and the reliability of cable connection is improved by adding additional cables. The additional cables are found by the PSO algorithm. Additional cables can ensure that the power generated by the WT can still be transmitted when a failure occurs in one cable. Taking the cable current carrying capacity into consideration, the type of additional cable in a branch are consistent with those already in this branch. The specific practice is shown in the following two cases. The dashed line indicated by the arrow represents two cables. One of the two cables is the additional cable. Solid lines of different colors represent various types of cables as given in table 1. The green rectangle represents the substation location in the wind farm and the red dots indicate the positions of the WTs.

1) REGULAR WIND FARM

There are totally 24 WTs in a regular wind farm. In the first step, the original cable connection is shown in FIGURE 6. By adding the additional cables, the final hybrid cable connection structure is shown in FIGURE 7.

Solid lines of different colors represent various types of cables as given in Table 1. The green rectangle represents the substation location in the wind farm and the red dots indicate the positions of the WTs. The dashed line indicates by the arrow in FIGURE 7 represents two cables. One of the two cables is the original cable as shown in FIGURE 6. The other cable is addition cable found by the PSO algorithm. The type of the two cables is the same. To see the performance of proposed method, the results of regular wind farms are shown in Table 2.

TABLE 2. Results for regular wind farm.

	Initial cable layout	*Cable layout after adding cables*
Total cable length in wind farm, (km)	14.39	**15.23**
Total cable length for transmission, (km)	2.35	2.35
Total cable cost(MDkk)	25.73	**21.95**
Energy losses, (GWh)	6.13	6.13
Energy yields, (GWh)	261.64	261.64
Substation location, (km)	(1.56, 0.35)	(1.56, 0.35)
Availability	94.8%	**96.1%**
EENS (in 20 years), (GWh)	8.68	**7.91**
LPC_{rel},*(Dkk/MWh)*	203.96	**199.86**

The changes are represented in bold text. The total cable length in wind farm and total cable cost goes up as additional cables are added. Once the location of the substation is determined, it will not change. The distance between substation and high voltage substation will also not change. So the total cable length for transmission is the same as before. The hybrid cable connection structure is to ensure a safe operation of the collector system as much as possible. The EENS is reduced as the additional cable added. The corresponding reliability is also improved. The energy yields depend on WTs' locations and climatology because both of these conditions are the same. The energy yields remain the same. In branches where additional cables are added, the existing cables and additional cables do not work together. In trouble-free conditions, the switches for the extra cables are off. So the energy losses along the line will not change. Since the switching cost is much lower than the cable cost, the switching cost is ignored in this paper. It can be clearly found that

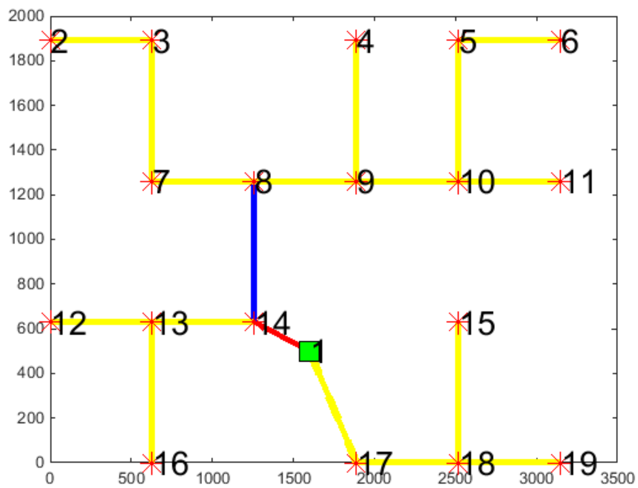

FIGURE 8. The initial cable connection in irregular wind farm.

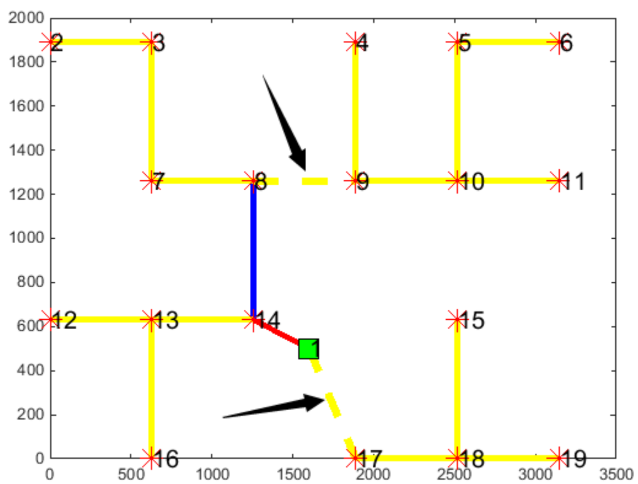

FIGURE 9. The final cable connection by adding cables in irregular wind farm.

the value of LPC_{rel} is reduced by adding cables. The ratio of the duration of no cable failure to the total operating cycle of a wind farm is availability.

2) IRREGULAR WIND FARM

There are totally 18 WTs in an irregular wind farm. The original cable connection and the final hybrid cable connection structure are shown in FIGURE 8 and FIGURE 9 respectively.

In the similar way to facilitate the data analysis, the results of irregular wind farms are shown in Table 3.

It can be seen that total cable length in the wind farm, total cable cost, availability, EENS and LPC_{rel} are changed. Indexes of change in this case are the same with regular wind farm. This shows that the reliability and economy of the collector system have been improved after the additional cables are added. The effectiveness of the proposed method is verified.

TABLE 3. Results for irregular wind farm.

	Initial cable layout	*Cable layout after adding cables*
Total cable length in wind farm, (km)	11.02	**12.23**
Total cable length for transmission, (km)	2.50	2.50
Total cable cost (MDkk)	20.44	**21.95**
Energy losses, (GWh)	4.50	4.50
Energy yields, (GWh)	199.92	199.92
Substation location, (km)	(1.6, 0.5)	(1.6, 0.5)
Availability	95.6%	**97%**
EENS (in 20 years), (GWh)	7.01	**6.38**
LPC_{rel}*,(Dkk/MWh)*	212.51	**209.43**

V. CONCLUSION

A new method is proposed in this paper to get a hybrid cable connection structure in order to obtain better reliability. The new method can be divided into two main steps. In the first step, to obtain the initial cable layout, a MST algorithm is proposed to connect all of the WTs to the substation. The obtained cable layout is radical topological structure. This kind of structure has better economy, but its reliability is weak. Then the reliability of the structure is analyzed by calculating EENS and the concept of LPC_{rel} is proposed. In the second step, the additional cables are found by the PSO algorithm. In the whole process of the PSO algorithm, the value of LPC_{rel} is set to judge the fitness of results. Finally, without changing the original cable selection and layout found by the MST algorithm, the value of LPC_{rel} is reduced after adding these additional cables. It indicates the reliability and economy of the final cable layout which is called a hybrid structure are better when EENS is considered. The hybrid structure proposed in this paper is to add additional cables to the original structure. In view of not changing the original cable structure, this method can be applied to other wind farm.

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