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Research on multi-objective optimal cable path design method based on differential evolutionary algorithm for transmission project boundary

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Abstract This paper proposes a multi-objective optimization method based on multiple group cooperative adaptive differential evolution algorithm (MCADE) for cable laying problems in power transmission engineering. A three-objective mathematical model containing the weight of the cable network, the percentage of the main road in the bundling section and the openness of the path is constructed, and the differential evolution algorithm is selected for path optimization. Adaptive multiple swarm strategy and multi-operator parallel search strategy are designed, and the improved MCADE algorithm is proposed. The MCADE algorithm simulates the actual situation of power pipeline network to establish the power laying network, and the MCADE algorithm performs the best among the three algorithms in solving the shortest paths of the two devices, which saves 16.88ms and 12.13ms compared with the ACA and ABC algorithms, respectively, and the average length of the paths in eight power cable laying tasks is only 45.13m, which reduces 45.37m and 68m, respectively, compared with the two traditional path planning methods for laying power cables. Compared with the two traditional power cable laying path planning methods, the average path length is only 45.13m, which reduces 45.37m and 68.78m respectively. The results confirm that the MCADE algorithm can effectively solve the multi-objective conflict problem in complex cable laying scenarios, which provides theoretical support and methodological reference for intelligent design of power projects.

Index Terms cable laying, multi-objective optimization, path optimization, differential evolutionary algorithm, MCADE algorithm

I. Introduction

As the artery of power transmission, the choice of laying method of transmission cable system has a profound impact on the performance, reliability and future scalability of the whole power system. In the current context of rapid growth in power demand and frequent access to new energy sources, stable power supply and efficient operation of the power grid are particularly critical [1], [2]. The advancement of urbanization and environmental protection requirements put forward higher standards for cable laying, especially in geographically complex and densely populated areas [3], [4]. This not only tests the adaptability of traditional laying techniques, but also promotes the exploration and application of new technologies, materials and methods. In the face of such a situation, exploring and analyzing high-voltage transmission cable laying methods suitable for the new era, aiming to enhance the overall performance of the power system while meeting the dual requirements of economic efficiency and environmental friendliness, has become an important issue in the design and planning of power systems [5]-[7].

In the traditional cable laying process, designers need to manually record the equipment wiring points for cable laying and the cable channels that can be used for wiring, and rely on the experience of the designers to plan the optimal path, and finally generate cable inventories and laying diagrams from the laying results [8]-[10]. This way basically all rely on human resources to realize, time-consuming and laborious, and it is difficult to obtain the optimal solution of cable laying to meet the engineering needs and save cable [11], [12]. In order to further improve the efficiency of cable laying, it is proposed to construct a cable path intelligent design model based on the algorithms of automatic generation of cable path nodes, intelligent calculation of cable path and optimal pushing of cable path [13]-[15]. By importing the three-dimensional entity environment and related data, the automatic generation of path nodes intelligently selects the optimal path of the cable, and then dynamically arranges the cable entities according to the path [16], [17]. Intelligent cable laying strategy adapts to the needs of the new period, provides scientific and reasonable reference basis for the planning and construction of the power system, and then promotes the technological progress and efficiency optimization of power grid construction [18].

This paper firstly describes the cable laying process and models the cable path multi-objective optimization problem. Adaptive multiple swarm strategies are designed to enhance the global search capability of the algorithm.

Propose the parallel search mechanism of multiple operators to improve the variation strategy of differential evolutionary algorithm. Design the model of electric power pipeline network for simulation analysis, and test the optimization ability of the proposed algorithm through case simulation. Test the time spent on algorithm path optimization to measure the performance level of MCADE algorithm. Select ACA and ABC algorithms as the control, and examine the superiority of MCADE algorithm in solving the cable path optimization problem by relying on the comparison of dual indicators.

II. MCADE-based multi-objective optimization cable path design methodology

II. A. Cable laying

Cable laying is a very important part of substation design. A large number of cables are like blood vessels and nerves, which are the guarantee for the safe and stable operation of the substation, and also bring great challenges to the cable laying. The requirements of cable laying are neat and beautiful in the line channel, saving cable, and the starting and stopping point and number of each cable are clear, in order to facilitate the subsequent cable maintenance and replacement, and effectively utilize the space in the channel and leave a margin for the subsequent expansion. Three-dimensional design can visually display the cable laying after the connection between the equipment and the cable channel, convenient for designers to view, if found unreasonable or error can be corrected in a timely manner.

Cable laying is a complex systematic work, not only contains the selection of cable calculations, but also need to lay the cable related facilities for the selection of calculations, and at the same time to choose the appropriate laying method according to its working environment. Commonly used cable laying methods are: direct burial, cable trench laying, shallow groove laying, cable tunnel laying and overhead laying. Substation cable laying generally take the cable trench laying, easy to lay the cable, maintenance and later expansion when increasing the cable. Substation cables mainly include power cables and control cables, power cables for high-voltage, high-current power transmission, power cable cross-section shown in Figure 1. Figure 1 mainly includes the conductor used to transmit power, the insulation layer between the conductor and the outermost protective layer. Power cable will produce a lot of heat during normal operation, more laid on the cable bridge, in order to facilitate the heat dissipation of the cable.

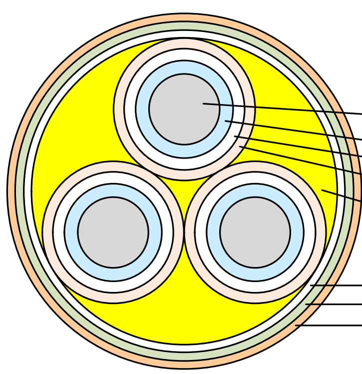

Figure 1: Section of power cable

II. B. Modeling the cable path multi-objective optimization problem

According to the layout design requirements of the cable network, this paper takes the weight of the cable network, the percentage of the main road in the bundling section, and the openness of the laying path area as the optimization objectives, and accordingly constructs the mathematical model of Eq. (1):

$$\begin{aligned} &\min f(p) = \left(f_1(p), f_2(p), f_3(p)\right)^T \\ &s.t. h(p) = 0 \\ &T(p) = 0 \\ &E(p) = 0 \\ &N(p) = 0 \\ &b(p) \geq b_{\min} \\ &s \in [2, n-2] \end{aligned} \tag{1}$$

where, $f_1(p)$ is the cable network weight objective function; $f_2(p)$ is the bundled segment trunk road share objective function; $f_3(p)$ is the laying path region openness objective function; $h(p)$ is the wall constraint, the path is close to the wall $h(p)=0$, and vice versa, $h(p)\neq 0$; the path does not pass through high temperature region $T(p)=0$, and vice versa, $T(p)\neq 0$; the path does not pass through the strong electromagnetic region $E(p)=0$, and vice versa, $E(p)\neq 0$; the port extension length meets the requirements $N(p)=0$, and vice versa, $N(p)\neq 0$; $b(p)\geq b_{\min}$ is the path to meet the minimum bending radius requirements; s is the number of branch points; n is the number of terminals; p is the cable layout scheme.

(1) Objective function $f_1(p)$ for cable network weight

The objective function $f_1(p)=G_0$, using equation (2) to calculate the total weight of cable network G_0 into two parts: the total weight of bundled section G_B and the total weight of unbundled section G_S :

$$G_0 = G_B + G_S \tag{2}$$

Recording information about the branching points through which a single cable passes allows the type and number of cables contained in each bundle segment to be calculated, and the total weight of the cables in the bundle segment to be solved for based on the lengths of the individual bundle segments using equation (3):

$$G_B = \sum_{i=1}^{n}\left(L_i \cdot \sum_{j=1}^{N_i}\rho_j\right) \tag{3}$$

where n is the number of bundled segments; L_i is the length of the bundled segment; N_i is the number of cables contained in the bundled segment; and ρ_j is the line density of the j th cable in the bundled segment.

The total weight of the cables in the unbundled section is calculated by the cable type and cable length of each unbundled section using equation (4):

$$G_S = \sum_{i=1}^{n} L_i \cdot \rho_i \tag{4}$$

where n is the number of unbundled segments; L_i is the length of unbundled segments; ρ_i is the line density of the i th cable.

(2) Objective function $f_2(p)$ for the trunk share of bundled segments

In order to ensure that the objective function $f_2(p)$ is a minimum value function, the constant K_1 is introduced so that $f_2(p)=K_1/\mathrm{Pr}oportion$, $\mathrm{Pr}oportion$ is the proportion of trunk road in the bundled section, which is calculated by adopting equation (5):

$$\mathrm{Pr}oportion = \frac{\sum_{i=1}^{n} L_i \cdot N_i}{\sum_{i=1}^{n} L_i} \tag{5}$$

where n is the number of bundled segments; L_i is the length of the i th bundled segment; N_i is the number of cables in the i th bundled segment.

(3) Laying path region openness objective function $f_3(p)$.

In order to ensure that the objective function $f_3(p)$ is also a minimum value function, the constant K_2 is introduced so that $f_3(p)=K_2/Openness$, and $Openness$ is the openness space of the cable path, which is computed by using equation (6):

$$Openness = \sum_{i=1}^{n} O_i \tag{6}$$

where n is the number of node units through which the cable passes; O_i is the open space around the node units, which is obtained from equation (7):

$$O = \sum_{i=1}^{n} V_i \tag{7}$$

where n is the number of neighboring node units; V_i is the volume of the unit.

The cable lengths L of both the bundled and unbundled sections above are Euclidean spatial distances, which are calculated using equation (8):

$$L = \sum_{i=1}^{n-1} \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2 + (z_{i+1} - z_i)^2} \tag{8}$$

where n is the number of node cells on the path; (x, y, z) are the coordinates of the center point of the cell.

II. C.Multiple swarm cooperative adaptive differential evolutionary algorithm design

In order to overcome the problems of premature convergence and search stagnation of DE algorithms in solving complex problems, and to improve the probability of the algorithms converging to the global optimal solution, this paper designs the multiple swarms collaborative adaptive differential evolution algorithm (MCADE) on the basis of the existing state-of-the-art differential evolution algorithms, MCADE proposes an improvement scheme for both the population structure and mutation strategy of the original algorithms, i.e., adaptive multiple swarms strategy and multiple operator parallel search strategy. The adaptive multi-population strategy is responsible for the adaptive division of sub-populations, balancing the global search and local development ability of the algorithm; the multi-operator parallel search strategy is mainly based on the tasks of the sub-populations, and the three variant operators with different search performance are used at the same time to generate the offspring individuals, which further strengthens the ability of the algorithm to explore and develop.

II. C. 1) Adaptive multiple swarm strategies

With the increasing complexity of optimization problems, the large number of local optima in the search space greatly increases the difficulty of the DE algorithm in finding the global optimal solution. In recent years, the distributed multiple swarm technique has achieved outstanding results in balancing algorithmic diversity and convergence, and has been proved to be effective in solving optimization problems with complex search space, and has become a popular improvement method that can significantly enhance the performance of DE algorithm, but the existing subpopulation division and cooperative exchange schemes are still not simple and efficient enough, so MCADE proposes an adaptive multiple swarm strategy to achieve the adaptive division and cooperation of sub-populations.

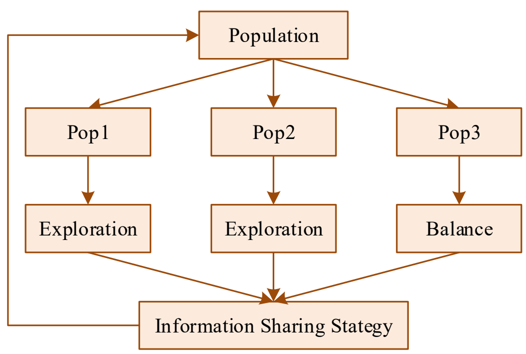

Figure 2: Adaptive multi-population strategy

The structure of the adaptive multiple population strategy is shown in Fig. 2. First, the MCADE algorithm randomly and evenly divides the initial population into an exploring subpopulation, an exploiting subpopulation, and a balancing subpopulation, and then each of the three subpopulations adopts a variant strategy with different performances to independently evolve in parallel, i.e., the exploring subpopulation Pop1 is responsible for driving the algorithm to search for a feasible solution within a larger range in order to quickly lock in the promising search intervals and at the same time maintain the diversity of the population; the exploitation sub-population Pop2 searches precisely near the optimal individuals of the population to improve the convergence of the population; the balancing sub-population Pop3 assists the searching sub-population to expand the search range in the early stage of evolution, and assists the exploiting sub-population to improve the convergence speed of the algorithm in the late stage of evolution, further balancing the convergence and diversity of the population. At the same time, the strategy can also check the evolutionary state of the algorithm by recording the number of times that the optimal individual of the population does not update consecutively, i.e., setting a threshold of the maximum number of stagnation times MS, when the number of times that the optimal individual does not update consecutively s exceeds MS, it is assumed that the current population has thoroughly developed the known search space, and the algorithm enters into the ineffective iteration, at which time the MCADE algorithm converges the three sub-populations and again randomly divides them equally and randomly selects individuals from the top 5% of the population fitness rankings to replace the worst individuals in each subpopulation, which is known as the adaptive information exchange mechanism.

Adaptive multi-population strategy firstly adopts parallel evolution to ensure that each sub-population is not interfered by other sub-populations in the process of executing the task, so as to take into account the exploration ability and exploitation ability of the algorithm, and at the same time, through a simple evolutionary state checking operation, the algorithm can adaptively complete the fusion of the sub-populations, the division of sub-populations, and the exchange of information, which effectively strengthens the algorithm's ability to overcome the stagnation of the search and the ability of the algorithm to jump out of the local optimum.

II. C. 2) Multi-operator parallel search strategy

In most of the improvement studies on differential evolution algorithms, researchers usually use a single general variational operator or propose a specialized variational operator applicable to the problem under study, however, these algorithms often do not perform well in solving optimization problems with different types of objective functions, so in order to enhance the generality of the algorithms, the simultaneous use of a single variational operator can easily lead to the algorithm falling into a local optimum. MCADE algorithm, on the other hand, based on the search task of three sub-populations, designs a multi-operator parallel search strategy, which uses three variant operators with different performances to find the global optimal solution at the same time in the evolution process, and solves the optimization problems with different characteristics through the advantages and cooperation of each operator, and the specific settings of the three variant operators are given below.

The search sub-population Pop1 adopts $DE/rand/2$ as the mutation operator, compared with the classical mutation operator $DE/rand/1$, this strategy randomly selects 5 individuals $x_{r_1} \sim x_{r_5}$ from the population, which results in 2 random difference vectors with mutation factors, and therefore its perturbation ability to the basis vectors is much stronger, and at the same time, since the operator has no constraint on search direction, its global search ability is stronger, which can significantly improve the search range of the algorithm and maintain the population diversity. The $DE/rand/2$ strategy is shown below:

$$v_{i,G} = x_{r_1,G} + F \cdot (x_{r_2,G} - x_{r_3,G}) + F \cdot (x_{r_4,G} - x_{r_5,G}) \tag{9}$$

Developing the sub-population Pop2 uses the variation operator $DE/rand \cdot best/2$, which can fully search the region around the current population optimal individual x_{best}, has good local exploitation ability, and facilitates the convergence of the whole population, and compared to $DE/best/1$, this variation operator uses 2 difference vectors with a variation factor, which improves the ability of the sub-population to jump out of the local optimum, and an additional weight factor α is added to the basis vector to further weaken the influence of the current optimal individual x_{best} on the subgeneration of the individual, preventing the algorithm from converging prematurely in the pre-evolutionary period due to the strong local search ability, the specific settings of the variation operator are shown below:

$$v_{i,G} = \alpha \cdot x_{best} + F \cdot (x_{r_1,G} - x_{r_2,G}) + F \cdot (x_{r_3,G} - x_{r_4,G}) \tag{10}$$

The balanced subpopulation Pop3 generates offspring using a combinatorial variation operator that mixes two different variation strategies using the evolutionary factor w: $DE/rand/1$ and $DE/current-to-best/1$, where $DE/rand/1$ serves as the classical variation operator, and all the individuals in this operator are generated randomly, It means that it has no specific search direction, so it has better global breadth search performance; $DE/current-to-best/1$, on the other hand, uses the individual x_i as the basis vector, which is perturbed by a fixed difference vector $\left(x_{best} - x_i\right)$ and a stochastic difference vector, and this operator is relatively strong in local depth search, and in this paper, we use the evolutionary coefficient w to combine the the advantages of the two variational operators are combined in order to obtain a variational operator with a relatively balanced performance of global search and local exploitation, which is set up as follows:

$$\begin{aligned} v_{i,G} = {} & (1-\omega) \cdot \left(x_{r_1,G} + F \cdot (x_{r_2,G} - x_{r_3,G})\right) \\ & + \omega \cdot \left(x_{i,G} + F \cdot (x_{best} - x_{i,G}) + F \cdot (x_{r_4,G} - x_{r_5,G})\right) \end{aligned} \tag{11}$$

where the evolution factor $\omega = g/G$, g represents the current generation index, and G is the maximum number of iterations of the algorithm. In the pre-evolutionary stage, $DE/rand/1$ in the variation operator (11) plays a dominant role, when the balancing sub-population can assist the exploring sub-population to search for potentially feasible solutions in a larger range; as iterations go on, the evolution factor w increases gradually As the iteration progresses, the evolutionary factor w gradually increases, and at the late stage of evolution, $DE/current-to-best/1$ plays a decisive role, and the equilibrium sub-population assists the explorer sub-population in accelerating the convergence of the population to the optimal solution. In conclusion, the purpose of the variation strategy (11) is to further maintain the population diversity and to increase the convergence speed of the algorithm, preventing the algorithm from falling into local extremes due to a particular variation strategy that has a decisive role in the evolutionary process.

III. Application analysis of MCADE-based multi-objective optimization cable routing approach

In the research process of cable laying method to simulate the actual situation of the power pipe network to establish the power laying network, the cable laying process is not strong in the degree of relevant laying factors to simplify and deal with a simplified power pipe network model. The model is set in the substation out of the station and the end of the cable laying, by the principle of the circuit can be known in the same cable line can be known to all the city nodes between the current value is equal, according to the barrel effect can be known to take the load capacity of the power cable between the nodes of the line laid between all the optimal load capacity of the lowest value. In the cable laying network, in order to simulate the scene of cable laying, the cable substation outlet area and the terminal area of cable laying are set.

III. A. Optimization ability test

In the cable path plan, arbitrarily select three devices for laying, find the shortest path among them, take device 1, device 5 and device 9 as an example, the three devices cable path optimization plane as shown in Fig. 3, there are a total of a variety of laying paths, the length of the various paths varies. The MCADE algorithm produces the result L = 113, which is verified to be in line with the shortest path requirements.

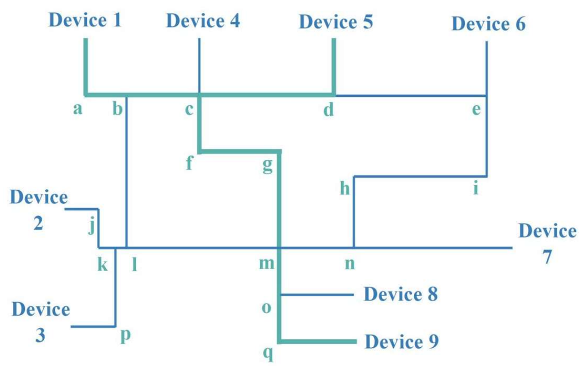

Figure 3: Cable path optimization plan for three equipments

Arbitrarily select four devices for laying, find the shortest path among them, take device 1, device 5, device 7 and device 9 as an example, the four device cable path finding plane is shown in Fig. 4, there are a variety of laying paths in total, the length of each path varies. The MCADE algorithm produces the result of L = 152, which is verified to be in line with the shortest path requirement.

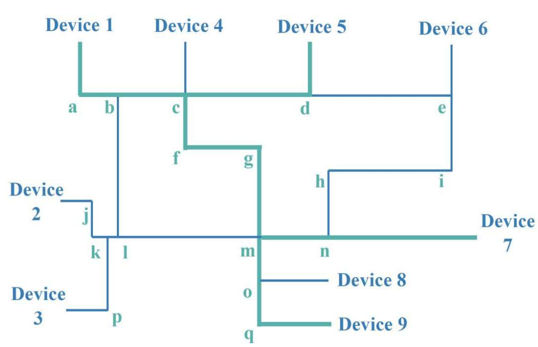

Figure 4: Cable path optimization plan of four equipments

III. B. Operational performance analysis

System.Diagnostics.Stopwatch function in C# is used in the algorithm performance test for program timing, where the starting point of timing is the entry point of Main function before the start of all the programs, and the end point of timing is the completion of all the programs, including data reading, data specification, path computation, output specification and verification logic.

The code is run 10 times consecutively, and the time spent on each path finding is recorded respectively, so as to measure the performance of MCADE algorithm.The time spent on 10 runs of MCADE algorithm is shown in Fig. 5, and according to Fig. 5, the average time spent in the run is 1587.47ms, and it can be seen that the algorithm's performance is more stable and less fluctuating.

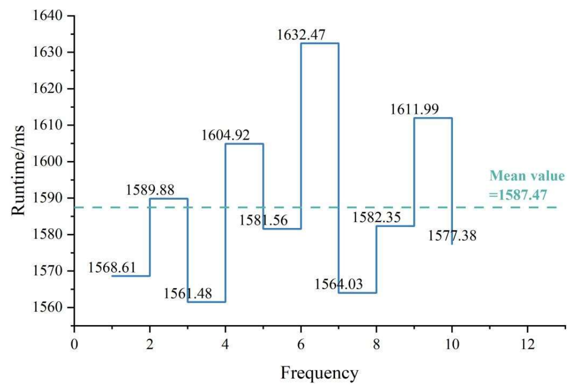

Figure 5: Results of 10 times running MCADE algorithm

The final laying result is shown in Fig. 6. It can be concluded that the cable laying path in the MCADE algorithm after optimization in the fourth iteration of the algorithm can be obtained cable laying path of the optimal solution of 206.15m, in the 22nd iteration of the algorithm after the cable laying path of the average laying distance tends to stabilize the value of 219.94m. In the algorithm's operation process to choose the 30 iterations as the maximum number of iterations of the MCADE algorithm at this time, the shortest distance is at the global optimal value and the average optimal path is 13.79m different from the value of the shortest path, and the time consumed for this operation is 1413.97ms.

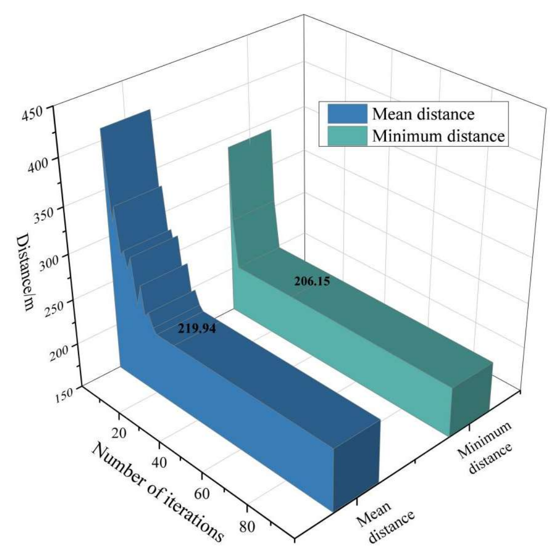

Figure 6: Path laying distance curve

III. C. Comparison of optimization results

In this section, the superiority of MCADE algorithm in cable laying optimization is verified by comparing it with the traditional Ant Colony Algorithm (ACA) and Artificial Bee Colony Algorithm (ABC) as shown in Table 1, which records the elapsed time and average elapsed time used by MCADE algorithm in finding the cable laying paths of two device nodes for eight times. The MCADE algorithm takes an average of 67.25ms to solve the shortest path of two devices, which is the best performance among the three algorithms, and saves 16.88ms and 12.13ms than the ACA and ABC algorithms, respectively.

Table 1: Comparison of time consumed by nodes (ms)

Number of experiments	ACA	ABC	MCADE
1	84	80	69
2	80	78	65
3	92	77	70
4	78	82	68
5	86	81	67
6	89	80	65
7	81	79	68
8	83	78	66
Mean value	84.13	79.38	67.25

Select 24 identical power cable laying tasks, and divide the power cable laying tasks into three groups, each containing eight tasks. This can reduce the experimental error to a certain extent and improve the stability of the experiment. Using three different methods to plan the power cable laying path, the path length comparison results are shown in Table 2. After analyzing the data in Table 1, it can be seen that the power cable laying path planning method designed in this paper shows significant advantages, and its average path length is only 45.13 m. The average path lengths obtained by the ACA algorithm and the ABC algorithm are 90.50 m and 113.91 m, respectively, and the MCADE algorithm reduces the average path lengths by 45.37 m and 68.78 m, respectively, compared with the two traditional power cable laying path planning methods. 45.37m and 68.78m of path length, which means that the method in this paper is more efficient in path planning.

Table 2: Results of path length comparison (m)

Task	ACA	ABC	MCADE
1	46.53	92.53	103.53
2	46.24	97.41	112.22
3	47.11	83.55	127.94
4	45.02	93.03	113.88
5	42.64	94.21	128.49
6	43.72	91.29	121.06
7	45.18	87.42	102.77
8	44.63	84.55	101.39
Mean value	45.13	90.50	113.91

In summary, the power cable laying path planning method designed in this paper is significantly better than the traditional planning method in terms of path length, which fully illustrates the practical application value of this paper's method in the power cable laying project, and provides a powerful tool and method reference for future power engineering construction.

IV. Conclusion

In this study, a multi-objective optimization cable path method based on MCADE is designed for the multi-objective optimization difficulties of cable paths in power transmission projects.

The simulation application shows that the average time consumed by the MCADE algorithm is 1587.47ms for 10 runs, and the optimal solution of cable laying path 206.15m is obtained in the 4th iteration of the algorithm, and the average laying distance of the cable laying path tends to be stabilized to 219.94m after the 22nd iteration of the algorithm.The comparative experimental results show that, MCADE algorithm performs best among the three algorithms in solving the shortest paths of the two devices, saving 16.88ms, ABC and ACA respectively, compared with ACA and ABC algorithm. The MCADE algorithm has the best performance among the three algorithms, saving 16.88ms and 12.13ms compared with the ACA and ABC algorithms respectively, and the average path length in 8 power cable laying tasks is only 45.13m, which reduces the path lengths by 45.37m and 68.78m respectively compared with the two traditional power cable laying path planning methods, which means that the method of this paper is more efficient in the path planning. This means that the method in this paper is more efficient in path planning.

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