Research Article

Numerical Study of Heat Transfer in Trefoil Buried Cable with Fluidized Thermal Backfill and Laying Parameter Optimization

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Trefoil buried cable is one of the important cable arrangements for the underground transmission line, and its heat transfer performance is relatively poor. By filling with fluidized thermal backfill material (FTB) around trefoil buried cables, the heat transfer would be efficiently enhanced, while the filling cost should also be considered. In the present study, the heat transfer process in the FTB trefoil buried cables is numerically studied, where the cable core loss and eddy current loss in the cable were coupled for the simulation. The heat transfer performances and ampacities for trefoil buried cables with different back fill materials were analysed and compared with each other. Then, the laying parameters for the parabolic-type FTB trefoil buried cables were optimized with the radial basis function neural network (RBNN) and genetic algorithm (GA). Firstly, it is found that, with FTB material, the maximum temperature in the cable core is obviously reduced, and the cable ampacity is greatly improved as compared with the cables buried around natural soil (NS). Secondly, when compared with flat-type FTB model, the heat transfer rate in the cable with parabolic-type FTB laying method would be slightly reduced, while the FTB amount used for the buried cables is greatly reduced. Finally, as for parabolic-type FTB trefoil buried cables, with proper design of geometric parameters ($s_1 = 0.290$ m, $s_2 = 0.302$ m, and $l = 0.3$ m with $I = 1300$ A) for the FTB laying cross section, the overall performance for the cable was optimized.

1. Introduction

As global economics increases, the demand for electricity supply increases rapidly [1]. The electrical energy is mainly transported through power cables, including overhead power cable and underground power cable. The overhead lines are often used for long distance electric power transmission, while the underground line usually plays an important role in the area near the city or some other special areas. For buried cables, the costs for laying and maintenance are usually much higher than those of the overhead cables [2, 3]. Therefore, for buried cables, the safety and cost issues should be considered simultaneously. During actual operation process, the surrounding soil near the buried cable will be heated and the soil will become dryer. This will drastically reduce the soil conductivity and directly affect the heat transfer in the cable system [4, 5]. In order to avoid soil desiccation and overheating of cables, the fluidized thermal backfill material (FTB) would be filled around the cables, which

would efficiently improve heat transfer rate for the buried cable system [6]. FTB material is an engineered slurry backfill mixture, which comprises fine and coarse natural mineral aggregates constituting the bulk volume of the mixture, cement providing the interparticle bond and strength, and fluidizer to impart a homogeneous fluid consistency for ease of placement [4, 6]. However, it should be noted that the cost of FTB laying method is much higher than that of natural soil (NS) laying method. Therefore, when the FTB laying method is used, not only heat transfer process in the cable system should be investigated, but the laying parameters should also be optimized to reduce the FTB laying cost.

Recently, the heat transfer performance in the buried cables has been widely studied by many researchers. Ochoń et al. [6] have numerically studied the heat transfer performance in the flat-type FTB trefoil buried cables. It was found that the heat transfer rate was efficiently improved when the FTB material was used for the buried cables. The effects of the backfill material amount and thermal conductivity on

the cable ampacity were numerically studied by León and Anders [7] with the finite element method (FEM). They found that the cable ampacity would be improved as the backfill material amount and thermal conductivity increased. The soil desiccation phenomenon around buried cables has been investigated by Gouda and Dein [8]. The thermal properties of eleven different backfill materials were analysed and the most suitable backfill material was obtained. Rerak and Ocloń [9] have numerically investigated the heat transfer performance in the trefoil buried cables with FEM method, where the thermal conductivities of soil and backfill material were related to the temperature variations. In their research, the effects of the backfill material thermal conductivity and cable core current on the maximum temperature of cables were carefully analysed. Furthermore, the moisture and temperature distributions of the backfill material surround the buried cables were numerically studied by Anders and Radhakrishna [10], and their numerical results could agree well with experimental data. In addition, researches on the optimization of laying parameters for buried cables are also popular in recent years. Ocloń et al. [11] have optimized the laying parameters for flat-type buried cables by using improved Jaya algorithm combined with FEM method. It was found that the improved Jaya algorithm would be more accurate and efficient for the optimizations. Cichy et al. [12, 13] have optimized the laying parameters for both the flat-type and the trefoil-type buried cables by using genetic algorithm (GA). With this method, the optimum laying parameters were obtained for the minimum laying cost. Saud [14] has optimized the laying parameters for the flat-type buried cables by using particle swarm optimization method (PSO). With this method, the optimum laying parameters were obtained for different object functions, including the maximum temperature, laying cost, and ampacity of buried cables. Furthermore, Ocloń et al. [4] have also optimized the laying parameters for the flat-type buried cables by using particle swarm optimization method (PSO). In their study, the thermal conductivities of soil and backfill material were related to the temperature variations, and the optimum laying parameters were finally obtained combined with experimental results [15].

Based on above literature survey, it shows that the researches on the heat transfer performance of buried cables and the corresponding optimizations of laying parameters were popular in the recent years. However, all these researches were mainly focused on the flat-type buried cables, and the researches on the heat transfer and optimization for the trefoil-type buried cables were relatively few. Trefoil buried cable is one of the important cable arrangements for the underground transmission line. It is often used in the situation with limited construction space and its heat transfer performance is relatively poor. By filling with fluidized thermal backfill material (FTB) around trefoil buried cables, the heat transfer would be efficiently enhanced [16], while the filling cost of FTB should also be considered. In the present paper, the heat transfer process in the flat-type FTB trefoil buried cables was numerically studied first, and the results were compared with those of flat-type NS trefoil buried cables. Then, the heat transfer process in the

parabolic-type FTB trefoil buried cables was numerically studied, and the results were compared with those of flat-type FTB trefoil buried cables. Finally, the laying parameters for the cross section of parabolic-type FTB trefoil buried cables were optimized with the radial basis function neural network (RBNN) and genetic algorithm (GA), and the optimum laying parameters and minimum total cost function were obtained. According to the authors' knowledge, almost no study was performed on the heat transfer process in the parabolic-type FTB trefoil buried cables before, and the results would be meaningful for the optimal design for the FTB trefoil buried cables.

2. Methodology

2.1. Model and Geometric Parameters. The model of trefoil buried cables with fluidized thermal backfill material (FTB) is presented in Figure 1. It includes the flat-type FTB trefoil buried cables (Figure 1(a)) and parabolic-type FTB trefoil buried cables (Figure 1(b)). The length (L) and height (H) of the computational domain are 20 m and 10 m, respectively. Three-phase cables are installed in a rectangular trench with width of 1.4 m. The distance between the trench top surface and the lower cable core is 1 m. As for the flat-type FTB trefoil buried cables (Figure 1(a)), the FTB thickness is h and the distance between the trench bottom surface and the lower cable core is 0.2 m. As for the parabolic-type FTB trefoil buried cables (Figure 1(b)), the distance between the FTB top point and the upper cable core is s_1 , the distance between the FTB bottom surface and the lower cable core is s_2 and the FTB width is $2l$. Besides FTB region, the other computational domain is filled with the natural soil (NS).

The arrangement of trefoil power cables and cable structure are presented in Figure 2. It shows that the trefoil power cables are stacked in a triangular arrangement (Figure 2(a)), where the cable diameter is d_i . In order to improve the computational mesh quality near the contact points between cable surfaces, the cables were assumed to be stacked with very small gaps ($l_1 = 2\%d_i$) instead of contact points between each other. Furthermore, as shown in Figure 2(b), the power cable is composed of copper conductor, insulation layer, sheath layer, and Jacket layer, where the corresponding radii are r_c , r_i , r_s , and r_j , respectively. Typical geometric and physical parameters of trefoil cables are listed in Table 1.

2.2. Governing Equations and Computational Method. In the present study, the heat transfer in the buried cables can be regarded as two-dimensional steady heat conduction process. The power cable is composed of copper conductor, insulation layer, sheath layer, and Jacket layer, and the heat loss is produced in the copper conductor and sheath layer, named as conductor loss and eddy loss, respectively. The heat transfer equation for the computational domain is as follows:

$$k \cdot \nabla^2 T = \begin{cases} -q_v, & \text{Cable core and sheath layer} \\ 0, & \text{Insulation layer, jacket layer, NS and FTB regions} \end{cases} \quad (1)$$

FIGURE 1: Model for FTB trefoil buried cables. (a) Flat-type FTB trefoil buried cables. (b) Parabolic-type FTB trefoil buried cables.

FIGURE 2: Power cables in trefoil arrangement and cable structure. (a) Power cables in trefoil arrangement. (b) Power cable structure.

where k is the thermal conductivity. q_v is the heat loss of power cable. The thermal conductivities of NS and FTB material (k_{NS} and k_{FTB}) are dependent on temperature variations, which are defined as follows [6, 17]:

$$k(T) = k_{dry} + (k_{wet} - k_{dry}) \cdot \exp \left[-a_1 \left[\frac{(T - T_{ref})}{(a_2 \cdot T_{lim})} \right]^2 \right] \quad (2)$$

$$a_1 = \frac{T_{lim}}{T_{ref}}$$

$$a_2 = 1 - \left(\frac{1}{a_1} \right)$$

where k_{dry} and k_{wet} are the thermal conductivities under dry and wet conditions for NS and FTB material (Table 2). T_{lim} is the limited temperature of power cable (363 K). T_{ref} is the reference temperature of surrounding soil (293 K). The

variations of the thermal conductivity of NS and FTB are presented in Figure 3.

The heat loss of power cable (q_v) is defined as follows:

$$q_v = \frac{|\vec{J}|^2}{\sigma} \quad (3)$$

where $\vec{J}$ is the total current density in the cable and σ is the electronic conductivity, which are defined as follows:

$$\vec{J} = \vec{J}_e + \vec{J}_s \begin{cases} \vec{J}_s > 0 & \text{Cable core} \\ \vec{J}_s = 0 & \text{Sheath layer} \end{cases} \quad (4)$$

$$\vec{J}_s = -\sigma \nabla \varphi,$$

$$\vec{J}_e = -j\omega\sigma\vec{A}, \quad (5)$$

$$\sigma = \frac{1}{\rho_0 (1 + \alpha (T - T_{ref}))}$$

TABLE 1: Typical geometric and physical parameters of trefoil cables (cable quadrature = 1600 mm²).

Cable	Radius [mm]	Material	Thermal conductivity [W/(m·K)]	Electronic conductivity [S/m]
Cable core	24.8	copper	400	5.998×10^7
Insulation layer	55.3	XLPE	0.38	1.0×10^{-15}
Sheath layer	61.7	copper	400	5.998×10^7
Jacket layer	66.8	HDPE	0.38	1.0×10^{-15}

FIGURE 3: Variations of k_{NS} and k_{FTB} with temperature.TABLE 2: k_{dry} and k_{wet} for NS and FTB material [6, 17].

Material	k_{dry} [W/(m·K)]	k_{wet} [W/(m·K)]
NS	0.30	1.00
FTB	1.54	4.35

where $\vec{J}_e$ is the inductive current density. $\vec{J}_s$ is the source current density. $\vec{A}$, j , ω , and ϕ are the magnetic vector potential, unit of complex number, angular frequency, and electric scalar potential, respectively. ρ_0 and α are the electrical resistivity and temperature coefficient at a reference temperature of $T_{ref} = 293$ K.

The boundary conditions for the computational domain are set as follows:

$$\begin{aligned}
 \left. \frac{\partial T}{\partial x} \right|_{x=0 \text{ or } x=L} &= 0, \\
 \left. \frac{\partial T}{\partial y} \right|_{y=0} &= 0, \\
 T|_{y=H} &= 293\text{K}
 \end{aligned} \tag{6}$$

In the present study, the above governing equations are solved with commercial code COMSOL MULTIPHYSICS, and the Pardiso solver is employed for the computations. The current frequency is set to 50 Hz. The conservative interface flux condition for heat transfer is adopted at the cable-FTB and FTB-NS interfaces, as well as the internal interfaces between different layers inside the cable, which means that the heat flux on one-side of the interface was considered to be equal to the heat flux on the other-side of the interface between

different computational regions. For convergence criteria, all residuals of the calculations are less than 10^{-4} .

3. Grid Independence Test and Model Validations

Firstly, the grid independence test was performed. In the present study, the parabolic-type FTB trefoil cables were adopted for the test ($s_1 = 3.5r_j$, $l = 8r_j$), where the cable core current is 1145 A and the current frequency is 50 Hz. As presented in Figure 4, the self-adaptive tetrahedral mesh was used for the computations, and the grids are intensified around cable regions. In order to improve the mesh quality near the contact points between cable surfaces, according to the report of Bu et al. [18], the cables were stacked with very small gaps ($l_1 = 2\%d_j$) instead of contact points between each other (Figure 2(a)). Four sets of grids were used for the test, and the computational results are presented in Table 3. It shows that the Grid-3 with total element number of 19346 is good enough for the test based on the comparison of the maximum cable temperature (T_{max}) and heat flux on the cable surface (ϕ) with different grids. For Grid-3, the minimum length of the grid element in both the cable zone (Zone 1) and FTB zone (Zone 2) is 0.3 mm and it is 0.4 mm in the NS zone (Zone 3). Therefore, similar grid settings to the test grid of Grid-3 were employed for the following simulations.

Subsequently, the computational model and methods were validated. The heat transfer process in three-phase buried cables [6] was restudied and the model is presented in Figure 5. It shows that the power cables are parallel arranged and the cable core distance is 0.4 m between each other. The distance between the ground and cable core is h_1 . In the near-cable region, the NS is used as the backfill material, while the other regions are filled with multilayer soil. The symmetry boundary condition is adopted on the left edge of the computational domain, and the right edge and bottom surface of the computational domain are considered to be adiabatic. Furthermore, the ground temperature is fixed at 293 K. The thermal conductivities of different backfill materials are dependent on temperature variations, which can be calculated with (2) and parameters listed in Table 4.

When the cable core current is fixed at 1145 A, the variations of temperature along the symmetry edge are presented in Figure 6(a). It shows that the maximum temperature deviation between our present computations and those of Ocłoń et al. [6] is 1.4 K. Meanwhile, the variations of the maximum cable core temperature (T_{max}) with cable buried depth (h_1) are presented in Figure 6(b). It shows that the maximum

FIGURE 4: Typical computational mesh for parabolic-type FTB trefoil buried cables.

TABLE 3: Computational results with different meshes.

Grid	Region	Minimum length of grid element [mm]	Maximum length of grid element [mm]	Total element number	$T_{\max}$ [K]	ϕ [W]
Grid 1	Zone 1	1.5	0.4	10228	326.56	68.899
	Zone 2	1.5	0.4			
	Zone 3	1.5	0.5			
Grid 2	Zone 1	0.4	0.2	16337	329.557	69.892
	Zone 2	1.5	0.4			
	Zone 3	1.5	0.4			
Grid 3	Zone 1	0.3	0.1	19346	329.563	68.903
	Zone 2	0.3	0.1			
	Zone 3	0.4	0.2			
Grid 4	Zone 1	0.3	0.1	28394	329.563	68.903
	Zone 2	0.3	0.1			
	Zone 3	0.35	0.15

FIGURE 5: Model for validations [6].

TABLE 4: Thermal conductivity of different buried material in Ocloń's study [6].

Material	k_{dry} [W/(m·K)]	k_{wet} [W/(m·K)]
NS	0.30	1.00
MS	0.21	2.28
Gr	0.26	2.67
SCLG	0.26	2.01
SCL	0.17	1.45

deviation of T_{max} between our present computations and those of Ocloń et al. [6] is 2.3 K.

4. Results and Discussion

4.1. Performance Comparison between NS and FTB Trefoil Buried Cables. When the cable core current is fixed at 1500 A, the temperature distributions in the trefoil buried cables with NS and flat-type FTB are presented in Figure 7. It shows that, for the NS trefoil buried cables (Figure 7(a)), since the thermal conductivity of NS material is relatively low (Figure 3), the heat transfer rate is relatively low and the maximum temperature of the cable core is high ($T_{max} = 448$ K or 175°C), while for the FTB trefoil buried cables (Figures 7(b)–7(d)), since the thermal conductivity of FTB material is relatively high (Figure 3), the heat transfer rate would be significantly improved and the maximum temperature of the cable core is obviously reduced. When the thickness of FTB is fixed at 0.4 m, 0.45 m, and 0.50 m, T_{max} of the cable core are 362 K (89°C), 357 K (84°C), and 353 K (80°C), respectively. The variations of the maximum cable core temperature in the trefoil buried cables with NS and flat-type FTB are presented in Figure 8. It shows that, with the same cable core current, T_{max} of the cable core for the NS trefoil buried cables is obviously higher than that for the FTB trefoil buried cables and T_{max} of the cable core for the FTB

trefoil buried cables would be further reduced as the FTB thickness (h) increases. In the present study, it is shown that the temperature distributions inside three-phase cables are quite similar for the same working condition. Therefore, the ampacities in the three-phase cables would also be similar. Here, the cable ampacity is defined as the corresponding current in the cable core when the maximum cable core temperature reaches 90°C (363 K). It shows that the cable ampacity for the NS trefoil buried cables is 1262.3 A, while the cable ampacities for the FTB trefoil buried cables are 1513.5 A ($h = 0.40$ m), 1558.2 A ($h = 0.45$ m), 1587.2 A ($h = 0.50$ m), and 1616.9 A ($h = 0.55$ m), respectively. Therefore, it is indicated that, for trefoil buried cables, the heat transfer rate would be efficiently improved by using FTB material, and the cable ampacity would be significantly increased.

The flat-type FTB trefoil buried cables as mentioned above (Figure 1(a)) are quite easy to be constructed. However, this FTB laying method needs large amount of FTB laying materials, which would lead to a certain waste. Therefore, in order to reduce the FTB amount used for the trefoil buried cables, the parabolic-type FTB laying method (Figure 1(b)) is adopted, and the heat transfer performance and ampacity of the parabolic-type FTB trefoil buried cables are analysed and compared with those of the flat-type FTB trefoil buried cables. Typical geometric parameters for flat-type FTB and parabolic-type FTB trefoil buried cables are presented in Table 5. It shows that, in the present study, the cross section area for the parabolic-type FTB model (A_{FTB}) is much lower than that for the flat-type FTB model.

When the cable core current is fixed at 1500 A, the temperature distributions in the flat-type FTB and parabolic-type FTB trefoil buried cables are presented in Figure 9. It shows that the temperature distributions in the flat-type FTB and parabolic-type FTB trefoil buried cables are similar, where the corresponding T_{max} of the cable core are 362 K (89°C) and 368 K (95°C), respectively. This indicates, with parabolic-type FTB laying method, the heat transfer rate in the cable would almost keep the same, while the FTB amount (represented by A_{FTB}) used for the trefoil buried cables can be greatly reduced.

The variations of the maximum cable core temperature (T_{max}) in the flat-type FTB and parabolic-type FTB trefoil buried cables are presented in Figure 10. It shows that, with the same cable core current, T_{max} of cable core for the parabolic-type FTB model is little higher than that for the flat-type FTB model, and the corresponding ampacities are 1477.5 A ($A_{FTB} = 0.351$ m²) and 1513.5 A ($A_{FTB} = 0.560$ m²), respectively. This indicates that compared with flat-type FTB model, the ampacity in the cable is slightly reduced with parabolic-type FTB laying method (reduced by 2.4% in the present study), while the FTB amount used for the buried cables (represented by A_{FTB}) is greatly reduced (reduced by 37.3% in the present study, Table 5). Therefore, the parabolic-type FTB laying method is recommended for the trefoil buried cable applications.

4.2. Laying Parameter Optimization for Parabolic-Type FTB Trefoil Buried Cables. The laying parameters for the parabolic-type FTB trefoil buried cables are presented in

FIGURE 6: Model validations for temperatures with Ocloń et al. [6]. (a) Temperatures along the symmetry edge. (b) The maximum temperature of cable core.

TABLE 5: Geometric parameters for flat-type FTB and parabolic-type FTB trefoil buried cables.

FTB laying model	s_1 [m]	s_2 [m]	l [m]	h [m]	A_{FTB} [m ²]
FTB (Parabolic)	$3.5r_j$	0.2	$8r_j$	/	0.351
FTB (Flat)	/	/	/	0.4	0.560

Figure 11. It shows that the FTB laying area (A_{FTB}) or FTB amount is closely related to the FTB laying parameters, mainly including s_1 , s_2 , and l . In order to enhance the heat transfer in trefoil buried cables and reduce the use of FTB material, the laying parameters should be optimized for the parabolic-type FTB trefoil buried cables. In the present study, the total cost function (F_c) as reported by Ocloń et al. [11] is adopted to access the overall performance for trefoil buried cables, which is defined as follows:

$$F_c(l, s_1, s_2) = \begin{cases} A_{\text{FTB}} + \text{PF} & T_{\max} - T_{\text{opt}} > 0 \quad (T_{\text{opt}} = 338\text{K}) \\ A_{\text{FTB}} & T_{\max} - T_{\text{opt}} \leq 0 \quad (T_{\text{opt}} = 338\text{K}) \end{cases} \quad (7)$$

where A_{FTB} is the FTB laying area. $T_{\max}$ is the maximum temperature of cable core. T_{opt} is the optimum working temperature for the cable ($T_{\text{opt}} = 338\text{K}$ or 65°C). PF is the penalty function. When the value of $T_{\max}$ is higher than that of T_{opt} (338 K), the penalty function (PF) should be set to guarantee the rationality of total cost function (F_c), where the PF is defined as follows:

$$\text{PF} = 10 \times (T_{\max} - T_{\text{opt}}) \quad (8)$$

Therefore, it should be noted that when the value of $T_{\max}$ is lower than that of T_{opt} , the total cost function (F_c) is depended

on A_{FTB} . Otherwise, F_c should be both related to A_{FTB} and $T_{\max}$.

In the present study, three geometric parameters of FTB laying cross section, including s_1 , s_2 , and l , were selected as the design variables, and the total cost function (F_c) is adopted as the objective function for the optimization. The flowchart for the optimization procedure is presented in Figure 12. Firstly, based on the design variables (s_1 , s_2 , and l), the geometric parameter combination samples were designed with the Latin hypercube sampling method (LHS) [19, 20]. LHS is an effective method to design sample points within the design space, by which the design points are equally spaced of each variable in design space [19]. When sampling a function of n variables, the range of each variable is divided into m equal probable intervals. For each variable, design points are randomly selected from each interval. Based on the m points for each variable, the sample points are obtained by the random combination. Hence, the design points are equally spaced of each variable in design space [19]. With this method, 50 sets of random samples were selected as the design samples for the optimizations, which are presented in Table 6. As shown in Table 6, both the ranges of s_1 and s_2 are from 0.1 m to 0.4 m, while the range of l is from 0.3 m to 0.7 m. Based on these 50 sets of samples, the heat transfer processes in the parabolic-type FTB trefoil buried cables were simulated with commercial code COMSOL MULTIPHYSICS. Then, the maximum temperature ($T_{\max}$) of the cable core and the total cost function (F_c) for the corresponding samples were

TABLE 6: Design samples with LHS method and the computational results of $T_{\max}$ and F_c ($I = 1300$ A).

Samples	s_1 [m]	s_2 [m]	l [m]	A_{FTB} [m ²]	$T_{\max}$ [K]	F_c
1	0.3843	0.3769	0.3117	0.3233	332.3360	0.3233
2	0.3181	0.3218	0.3565	0.3183	334.6860	0.3183
3	0.1562	0.2716	0.6180	0.4077	355.5410	175.8177
4	0.3818	0.3014	0.5370	0.5316	330.0740	0.5316
5	0.2238	0.2232	0.4746	0.3155	338.1350	1.6655
6	0.1128	0.2896	0.3806	0.2221	342.2830	43.0521
7	0.1604	0.3373	0.5287	0.3921	334.6920	0.3921
8	0.3733	0.1883	0.3684	0.2918	338.1560	1.8518
9	0.3564	0.1961	0.4594	0.3687	335.8680	0.3687
10	0.3014	0.2172	0.4194	0.3140	337.4600	0.3140
11	0.2902	0.3613	0.6789	0.6546	328.3190	0.6546
12	0.1001	0.1387	0.6094	0.2479	343.8940	59.1879
13	0.1322	0.1752	0.4716	0.2255	343.8250	58.4755
14	0.1508	0.2070	0.5538	0.3093	339.4900	15.2093
15	0.3458	0.2273	0.4407	0.3641	335.3500	0.3641
16	0.2356	0.3250	0.4092	0.3281	335.4600	0.3281
17	0.1934	0.3718	0.4042	0.3261	335.1620	0.3261
18	0.1763	0.1190	0.5951	0.2859	341.9510	39.7959
19	0.1854	0.1328	0.5425	0.2735	342.0180	40.4535
20	0.2569	0.1070	0.3248	0.1667	347.9650	99.8167
21	0.1383	0.1705	0.3164	0.1380	349.9190	119.3280
22	0.2917	0.1161	0.3972	0.2364	343.2150	52.3864
23	0.3084	0.2500	0.5218	0.4286	333.7690	0.4286
24	0.3242	0.1794	0.4314	0.3155	338.0940	1.2555
25	0.2048	0.3864	0.6011	0.5264	330.6140	0.5264
26	0.3900	0.3173	0.6881	0.7151	327.4050	0.7151
27	0.1692	0.2671	0.6513	0.4393	334.7680	0.4393
28	0.3359	0.1279	0.5774	0.4059	336.8790	0.4059
29	0.2382	0.2923	0.6391	0.5106	332.1900	0.5106
30	0.3548	0.3105	0.6294	0.6152	329.0470	0.6152
31	0.2127	0.3023	0.5580	0.4290	333.8130	0.4290
32	0.3296	0.2413	0.6464	0.5518	335.1400	0.5518
33	0.2035	0.1481	0.5005	0.2713	341.5770	36.0413
34	0.3635	0.3457	0.5641	0.5801	328.6610	0.5801
35	0.3443	0.1867	0.3929	0.2980	338.2780	3.0780
36	0.2591	0.2779	0.4456	0.3472	335.6430	0.3472
37	0.2461	0.3439	0.3002	0.2413	337.7180	0.2413
38	0.2195	0.2851	0.4870	0.3622	335.5940	0.3622
39	0.2712	0.2026	0.3484	0.2329	341.1970	32.2029
40	0.2303	0.3541	0.5037	0.4297	332.5610	0.4297
41	0.1175	0.1257	0.3597	0.1312	351.9180	139.3112
42	0.2642	0.3307	0.6724	0.5971	329.9080	0.5971
43	0.3056	0.3823	0.6227	0.6271	328.0290	0.6271
44	0.1912	0.2420	0.3305	0.2009	342.9110	49.3109
45	0.2527	0.2565	0.6677	0.5163	332.6100	0.5163
46	0.1246	0.1592	0.3740	0.1583	348.6010	106.1683
47	0.2746	0.3970	0.3427	0.3188	333.4970	0.3188
48	0.1778	0.3630	0.5872	0.4737	332.2980	0.4737
49	0.1092	0.2612	0.6948	0.4105	336.4770	0.4105
50	0.3695	0.2309	0.6618	0.5919	330.8430	0.5919

FIGURE 7: Temperature distributions in the trefoil buried cables with NS and flat-type FTB. ($I = 1500$ A). (a) NS buried cables. (b) Flat-type FTB buried cables ($h = 0.40$ m). (c) Flat-type FTB buried cables ($h = 0.45$ m). (d) Flat-type FTB buried cables ($h = 0.50$ m).

calculated based on the simulation results, which are also presented in Table 6.

Secondly, based on the sample data and calculation results as presented in Table 6, the geometric parameters for the parabolic-type FTB trefoil buried cables (s_1 , s_2 , and l) were trained with the radial basis function neural network (RBNN) [19–21]. RBNN is a two-layer network with strong ability to approximate objective function and rapid convergence rate, including a hidden layer of radial basis function (RBF) and a linear output layer [19]. Figure 13 shows the model of radial basis function neuron. The input n to the radial basis function is the vector distance between the input vector $\mathbf{x}$ and the weight vector $\mathbf{w}$, multiplied with a threshold value b .

$$n = \|\text{dist}\| \cdot b = \|\mathbf{w} - \mathbf{x}\| \cdot b \quad (9)$$

Gaussian function is employed as the radial basis function:

$$y = \text{radbas}(n) = e^{-n^2} \quad (10)$$

When n approaches zero, which means the input vector $\mathbf{x}$ and weight vector $\mathbf{w}$ are approximative, the output of the

radial basis function will be a relatively large value close to 1; thus the network has a strong ability of local perception. Figure 14 shows the whole structure of the radial basis neural network. The output of the network is a weighted sum of the outputs of hidden layers. The RBNN is established by using mathematical software MATLAB. The function of RBNN in MATLAB is `newrb`. Besides the sample data of inputs and outputs, a spread constant and the maximum number of neurons need to be determined. Spread constant is related to the threshold value b that controls the sensitivity of radial basis function neuron. Its value should be large enough to ensure the response within all the design space. However it should not be so large that all the neurons have significant response.

The maximum temperature ($T_{\max}$) of the cable core was predicted with RBNN and validated with commercial code COMSOL MULTIPHYSICS. The predicted values of $T_{\max}$ with RBNN and COMSOL MULTIPHYSICS for 10 sets of random samples are presented in Table 7. It is found that the maximum deviation of $T_{\max}$ with RBNN and COMSOL

TABLE 7: The comparison of $T_{\max}$ with RBNN and COMSOL ($I = 1300$ A).

Samples	Design variables			$T_{\max}$ [K]	
	s_1 [m]	s_2 [m]	l [m]	RBNN	COMSOL
1	0.3152	0.2035	0.3393	340.7534	340.095
2	0.1936	0.1294	0.5348	342.1368	342.075
3	0.3079	0.3779	0.4763	328.3667	330.314
4	0.3557	0.2250	0.5911	332.6455	332.348
5	0.2578	0.2849	0.5785	333.4514	332.856
6	0.2280	0.2790	0.4530	336.7406	336.332
7	0.3755	0.3126	0.4107	332.0261	332.229
8	0.1740	0.3672	0.6314	333.6398	331.612
9	0.1432	0.1645	0.6692	340.7285	339.486
10	0.1196	0.1443	0.3564	349.3775	350.652

TABLE 8: The optimum results with GA for parabolic-type FTB trefoil buried cables ($I = 1300$ A).

Population	Optimal design variables (GA)			$T_{\max}$ [K]		Fc
	s_1 [m]	s_2 [m]	l [m]	GA	COMSOL	GA
100	0.298	0.303	0.3	337.799	337.675	0.2456
200	0.290	0.302	0.3	337.998	338.076	0.2420

FIGURE 8: Variations of the maximum cable core temperature in the trefoil buried cables with NS and flat-type FTB.

MULTIPHYSICS is 2 K. Therefore, the prediction results with RBNN for the present study are reliable.

Finally, combined with RBNN, the genetic algorithm (GA) [22, 23] is used to optimize the geometric parameters for the parabolic-type FTB trefoil buried cables (s_1 , s_2 , and l), where the total cost function (F_c) is adopted as the objective function for the optimizations. Genetic algorithm (GA) can be easily used to get the maximum value or minimum value of a specific function. In the optimization, when GA is

performed, the RBNN acts as the objective function to be minimized. GA uses the theory of biological evolution, and it obtains the optimized point by a number of generations evolving from the initial population. Individuals of each generation are decided by the value of fitness function of each individual of the last generation and the randomness of selection, crossover, and mutation. The standard genetic algorithm (SGA) is conducted using the genetic algorithm toolbox of MATLAB. The predicted results of $T_{\max}$ with GA were also validated with commercial code COMSOL MULTIPHYSICS. When the cable core current is fixed at 1300 A, the optimum results with GA for the parabolic-type FTB trefoil buried cables are presented in Table 8. It shows that the values of the optimum geometric parameters (s_1 , s_2 , and l) of FTB cross section with GA are almost the same at populations of 100 and 200. When the population number is 200, the optimum values of s_1 , s_2 , and l are 0.290 m, 0.302 m, and 0.3 m, respectively, and the maximum temperature ($T_{\max}$) of the cable core is 337.998 K. The deviation of $T_{\max}$ predicted with GA and COMSOL MULTIPHYSICS is 0.078 K, and $T_{\max}$ is also quite close to the optimum cable working temperature ($T_{\text{opt}} = 338\text{K}$ or 65°C). With the optimum geometric parameters ($s_1 = 0.290$ m, $s_2 = 0.302$ m, and $l = 0.3$ m), the minimum total cost function (F_c) is 0.2420 for parabolic-type FTB trefoil buried cables.

5. Conclusions

In the present paper, the heat transfer process in the parabolic-type FTB trefoil buried cables is numerically studied, where the cable core loss and eddy current loss in the cable were coupled for the simulation, and the thermal conductivity of the backfill material was considered to be related to temperature variations. The heat transfer performances and ampacities for the flat-type NS, flat-type FTB,

FIGURE 9: Temperature distributions in flat-type FTB and parabolic-type FTB trefoil buried cables. ($I = 1500$ A). (a) Flat-type FTB buried cables ($A_{FTB} = 0.560$ m²). (b) Parabolic-type FTB buried cables. ($A_{FTB} = 0.351$ m²).

FIGURE 10: Variations of the maximum cable core temperature in flat-type FTB and parabolic-type FTB trefoil buried cables.

and parabolic-type FTB trefoil buried cables were carefully analysed and compared with each other. Then, the laying parameters for the cross section of parabolic-type FTB trefoil buried cables were optimized with the radial basis function neural network (RBNN) and genetic algorithm (GA). The main findings are as follows:

(1) Since the thermal conductivity of FTB material is relatively high, the heat transfer rate in the FTB trefoil buried cables would be significantly improved and the maximum temperature in the cable core is obviously reduced. Therefore, the ampacity for the FTB trefoil buried cables is much higher than that for the NS trefoil buried cables.

FIGURE 11: The geometric parameters of parabolic-type FTB trefoil buried cables.

FIGURE 12: Flow chart for the optimization procedure.

FIGURE 13: The model of radial basis function neuron.

FIGURE 14: The structure of radial basis neural network.

(2) When compared with flat-type FTB model, the heat transfer rate in the cable with parabolic-type FTB laying method would be slightly reduced, while the FTB amount used for the buried cables would be greatly reduced. When the cable core current is fixed at 1500 A, the ampacity in the cable is only reduced by 2.4% with parabolic-type FTB laying method, while the FTB amount is reduced by 37.3%. Therefore, the parabolic-type FTB laying method is recommended for the trefoil buried cable applications.

(3) For parabolic-type FTB trefoil buried cables, with proper design of geometric parameters (s_1 , s_2 , and l) for the FTB laying cross section, the overall performance of the cable would be optimized. When the cable core current is fixed at 1300 A, the optimum values of s_1 , s_2 , and l are 0.290 m, 0.302 m, and 0.3 m, respectively, the maximum temperature ($T_{\max}$) of the cable core is 337.998 K, and the minimum total cost function (F_c) is 0.2420.

Nomenclature

- a_1, a_2 : Model coefficients in (2)
 b : Threshold value in (9)
 A_{FTB} : FTB area, m^2
 $\vec{A}$: Magnetic vector potential, Wb/m
 d_j : The diameter of cable, m
 F_c : Total cost function
 h : The thickness of the flat-type FTB laying model, m
 h_1 : The distance between the cables and ground in [6], m
 H : The height of the computational model, m
 I : Cable core current, A
 j : Unit of complex number
 $\vec{J}$: Current density, A/m^2
 $\vec{J}_e$: Inductive current density, A/m^2
 $\vec{J}_s$: Source current density, A/m^2
 k_{dry} : Dry thermal conductivity of backfill material, $\text{W/(m}\cdot\text{K)}$

- k_{FTB} : Thermal conductivity of FTB, $\text{W/(m}\cdot\text{K)}$
 k_{NS} : Thermal conductivity of NS, $\text{W/(m}\cdot\text{K)}$
 k_{wet} : Wet thermal conductivity of backfill material, $\text{W/(m}\cdot\text{K)}$
 l : The distance between the edge of FTB and the axis of symmetry in the parabolic-type FTB laying model, m
 l_1 : Distance of the gap between cables, m
 l_s : Distance between two neighbor cable cores, m
 L : The width of the computational model, m
 n : Input to the radial basis function in (9)
 q_v : Heat loss, W/m^3
 r_c : The radius of conductor, m
 r_i : The radius of insulation layer, m
 r_j : The radius of jacket layer, m
 r_s : The radius of sheath layer, m
 s_1 : The distance between upper cable core and the top of FTB in the parabolic-type FTB laying model, m
 s_2 : The distance between the lower cable core and bottom of FTB in the parabolic-type FTB laying model, m
 T : Temperature, K
 T_{lim} : The limited temperature, K
 T_{max} : The maximum temperature, K
 T_{opt} : The optimum temperature, K
 T_{ref} : The reference temperature, K
 $\mathbf{w}$: Weight vector in (9)
 $\mathbf{x}$: Input vector in (9)

Greek Letters

- α : Reference temperature coefficient in (5)
 ρ_0 : Reference electrical conductivity, S/m^2
 σ : Electrical conductivity, S/m^2
 ϕ : Heat flux, W
 φ : Electric scalar potential, V
 ω : Angular frequency, rad/s

Subscripts

- c: Conductor
i: Insulation layer
j: Jacket layer
max: The maximum value
opt: The optimum value
ref: The reference value
s: Sheath layer

Abbreviations

- FEM: Finite element method
FTB: Fluidized thermal backfill
GA: Genetic algorithm
LHS: Latin hypercube sampling
NS: Natural soil
PF: Penalty function
PSO: Particle swarm optimization

RBF: Radial basis function
 RBNN: Radial basis neural network
 SGA: Standard genetic algorithm
 XLPE: Cross-linked polyethylene.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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