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On Reduction of Eddy Current Losses in a Double-circuit Junction Tower Through Cable Sequencing and Reconfiguration

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In modern cities, consideration must be given to both the development of electric energy and the improvement of landscape. Therefore, power technicians usually substitute underground cables for overhead lines. Moreover, junction towers are always employed to provide this interface between overhead lines and underground cables. This study focuses on reducing eddy current losses of a power junction tower. The losses in structural steels of a tower will be computed, and different cable arrangements are discussed by finite element method. Furthermore, the results indicate that eddy current losses of steels can be reduced by performing cable sequencing and reconfiguration without any new facilities. The reduction scheme can be useful for reducing eddy current losses of junction towers.

Keywords : junction tower, underground cable, eddy current loss, electromagnetic field, cross-linked polyethylene cable, finite element method

1. Introduction

Overhead power lines are major vehicles for long-distance electric transmission in rural areas. Nevertheless, in urban areas, the unsightly overhead lines are usually replaced with underground power cables for conforming the landscape or architectural designs. Therefore, facilities which can facilitate the transfer of power transmission between overhead lines and underground cables are essential. In fact, junction towers are always playing the important role in power delivery systems. They are always employed to provide an interface between underground cables and overhead lines, as illustrated in Fig. 1. Undoubtedly, they should be attached great importance.

A junction tower with six cross-linked polyethylene (XLPE) power cables is shown in Fig. 2. Junction towers are mainly constructed using high tensile angle steels, which have good magnetic permeability and are good conductors. Hence, the three-phase currents will produce an electromagnetic field as a result of inducing eddy currents inside the steels [1-5]. Therefore, the effective reduction of eddy current losses will be helpful in improving the efficiency of power delivery.

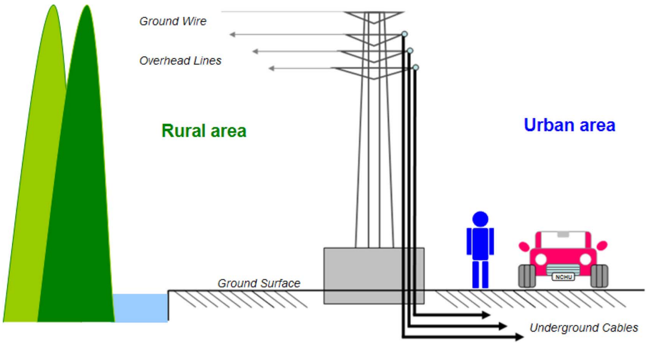

Fig. 1. (Color online) A sketch of a junction tower.

Although power junction towers are common in modern countries, there is scarce research investigating about junction towers. Hwang performed a thermal analysis of an underground XLPE-cables system and described a finite element method to investigate the effect of the steels' spacing on eddy current losses in the steels when nearby three-phase currents exist [3, 4]. Rachek *et al.* analyzed three-phase multi-circuit underground systems by extending the model of Hwang [3,4], and then effectively reduced the temperature of the cables system

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Fig. 2. (Color online) Junction tower with structural steels and cables.

[5]. Farag *et al.* investigated the problem of the electromagnetic field evoked by the power cables, and suggested several methods for reducing the field levels [6, 7]. By integrating their precious experience [3-7], we have presented a result for reducing magnetic fields of a junction tower with double circuits [8].

In practice, there are two prevalent cable installations which are usually applied in double-circuit junction towers. They can be distinguished by the installation in the top view of towers, as shown in Fig. 3 and 4. In this study, they are called Mode-Opp and Mode-Adj respectively. A Mode-Opp structure is shown in Fig. 3 and these two three-phase cable sets are installed opposite each other. Fig. 4 depicts an overhead view of a junction tower with double-circuit cables, demonstrating the Mode-Adj and these cable sets are installed adjacent to each other. As shown in Fig. 2, XLPE cables are almost installed in parallel with the tower body and the height of the tower is about 30 meters. Hence, there will be eddy current losses induced in structural steels of towers and these losses should not be ignored. This study conducts a finite element analysis [9, 10] to estimate the eddy current losses generated in steels of a junction tower.

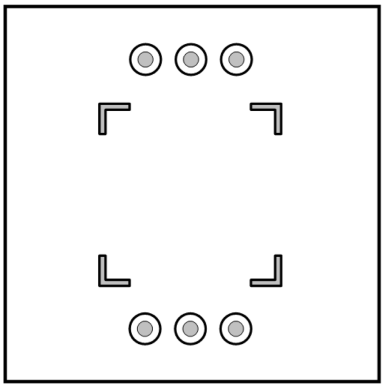


Fig. 3. Overhead view of a double-circuit junction tower, Mode-Opp.

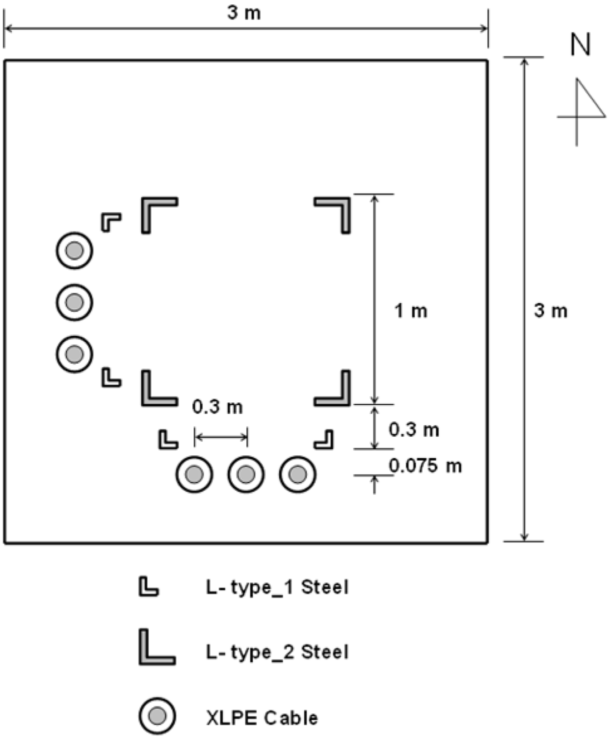


Fig. 4. Overhead view on a junction tower with double-circuit, Mode-Adj.

In this paper, the eddy current losses are calculated, and a technique of cable arrangement [6-8] to reduce the electromagnetic fields of junction towers with double-circuit cables is employed. The results of this study will contribute in the reduction of eddy current losses in steels of power junction towers.

2. Simulation of Junction Tower

2.1. Model of junction tower

As shown in the Fig. 1, the overhead power lines are connected to underground cables. This connection is

Table 1. Material Specifications for junction tower.

Components	Thermal conductivity (W/m°C)	Dimension	Electrical conductivity (S/m)
Conductor	386.0	0.001 m^2	5.8×10^7
Angle steel	19.0	200 mm(H) × 200 mm(W) × 25 mm(T)*	1.03×10^7
Angle steel	19.0	75 mm(H) × 75 mm(W) × 6 mm(T)*	1.03×10^7
Air (20 °C)	0.024		0

established with the construction of the junction tower before the entrance into the urban area, and then the urban landscape can be maintained.

In general, angle steels are used in the construction of power towers. Fig. 2 depicts a junction tower with cables and several L-type angle steel materials that increase the strength of the mechanical construction. Fig. 4 is a top view of a junction tower and there are eight L-type angle steel materials and six XLPE power cables on its base. The rated voltage and operating current of the XLPE cable are 161 kV and 650 A, respectively [3, 4, 8, 11]. Additionally, the relative material specifications of the junction tower are shown in Table 1. In this study, the towers with angle steels and XLPE cables will be analyzed and discussed. The magnetic field problem is solved by finite element method, which is performed using Magsoft Flux 3D [12].

2.2. Electromagnetic field equations

In practice, the XLPE power cables and steel materials for the tower are installed almost parallel with one another. Therefore, the magnetic problem can be converted to a two-dimensional problem. Furthermore, the analyses of this study are based on the following assumptions:

- The load currents are sinusoidal and balanced.
- Only the z-directional component of the magnetic vector potential, which is sinusoidal, can be observed.
- All materials have constant electricity and do not affect temperature.
- All materials have constant magnetic properties.

The magnetic vector potential must satisfy the following governing differential equations [3-5,8].

$$\nabla^2 \bar{A} = \partial(\partial\bar{A}/\partial x)/\partial x + \partial(\partial\bar{A}/\partial y)/\partial y = -\mu\bar{J}\ , \tag{1}$$

$$\bar{J} = -j\omega\sigma\bar{A} + \bar{J}_S\ , \tag{2}$$

$$\int_a \bar{J} \bullet d\bar{a} = I_i,\ I_i = I_A, I_B, I_C\ , \tag{3}$$

Employing the Galerkin procedure to Eqs. (1), (2), and (3) and the ordinary procedure to all the element contributions yields the following matrix equation [3, 8].

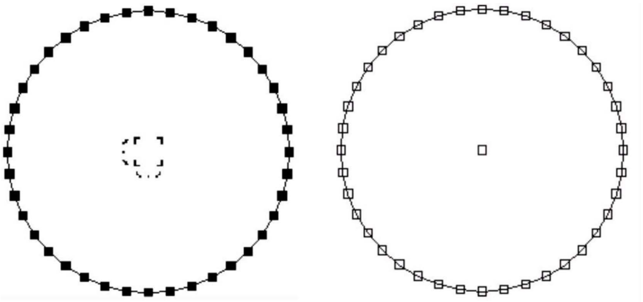


Fig. 5. Infinite domain is mapped onto finite domain.

$$\begin{bmatrix} S/\mu - j\omega\sigma R & -j\omega\sigma Q \\ -j\omega\sigma Q^T & j\omega\sigma W \end{bmatrix}\begin{bmatrix} A \\ G \end{bmatrix} = \begin{bmatrix} 0 \\ I \end{bmatrix} \tag{4}$$

Where the matrix G is equal to $(1/j\omega\sigma)J_S$, Q and W are the matrices obtained in the solution of Ref. [9], and S and R are listed in Ref. [10]. The eddy current loss in each steel can be calculated as follows [4, 8]:

$$q = \iint_\Omega (JJ^*/\sigma)\,d\Omega \tag{5}$$

This study performs a steady-state analysis. Hence, all magnetic fields are extended to infinity [8, 12-13]. To put it another way, this is an open boundary electromagnetic field problem, the boundary of the study domain must be placed sufficiently far from the junction towers so as not to have any effect on the results. As illustrated in Fig. 5, the space is subdivided into two subdomains, and the infinite exterior is mapped onto the finite domain by Flux3D [12].

3. Analysis and Discussion

In this study, phases a, b, and c are at 0, −2π/3, and 2π/3 rad, respectively. Moreover, the number of cable arrangements is equal to 3! (i.e. 6) in a single three-phase current system. Then, a total of 36 (i.e. 6^2) cable arrangements can be found in a double-circuit cable system.

3.1. Electromagnetic field analysis

Although each current of an ideal three-phase power system has the same effective magnitude, these different

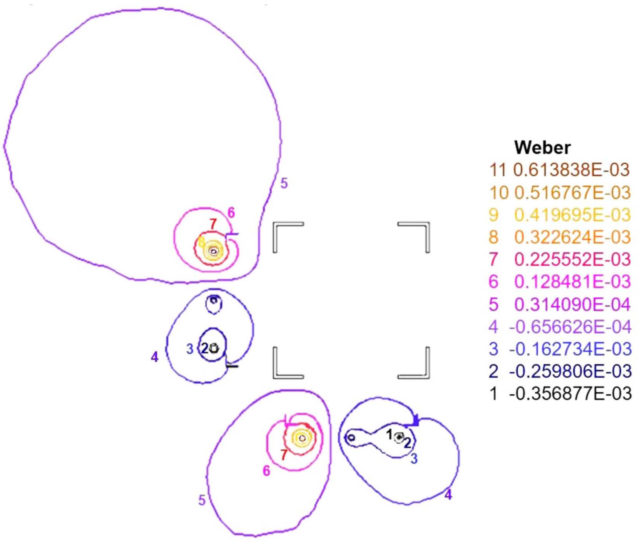


Fig. 6. (Color online) Contour of magnetic flux (as abc/abc configuration).

three-phase currents will produce different electromagnetic fields. The different direction components of the magnetic fields are interacted on each other, and then the resultant electromagnetic field is formed. Fig. 6 shows the contour of magnetic field distribution of this junction tower. In Fig. 6, the cables are installed in Mode-Adj using the abc/abc configuration.

3.2. Computation of eddy current losses in steel

After magnetic field is analyzed, all eddy current losses in the eight L-type steel structures are calculated and summed. For example, the loss in each steel structure of Group A1 is computed and listed in Table 2. The sum of the eight losses is also listed. Table 3 shows 36 different arrangements of Mode-Adj. The magnetic field is analyzed to determine the differences between the 36 cable arrangements. Table 3 presents the total eddy current losses in all the steel structures of different cable arrangements. In this table, ① denotes the maximal losses, and the other numbers represent the other recorded losses arranged in descending order. They are classified into six ranks. The cable arrangement of Rank ① is described as the sequences of two cable sets in reversed directions ("anti-sequence") in this paper. Fig. 7(a) illustrates the anti-sequence. Whereas, the cable arrangement of Rank ⑥ comprises the same sequence ("same-sequence"), as shown in Fig. 7(b).

The eddy current loss problem of Mode-Opp has discussed in Ref. [8]. To further realize the difference between these two modes, their maximal and minimal losses are shown in Table 4. As listed in Table 4, the maximal loss of Mode-Adj is more than the maximal one of Mode-Opp. The loss of Rank ⑥ in Mode-Adj is the minimum one and less than the minimal one of Mode-Opp. It indicates that the management of cable arrangement can effectively change eddy current losses in steels

Table 2. Eddy current losses (W/m) in the steels of Group A1.

No.	1	2
Loss in each steel	ⓐ 5.8509 ┌ 1.9231 ┌ ┐ 0.0117 ⓑ 3.9335 └ 0.8477 └ ┘ 1.3040 ⓒ 4.5845 └ ┘ 5.8932 ⓐⓑⓒ	ⓐ 5.1811 ┌ 1.4510 ┌ ┐ 0.0329 ⓑ 6.7183 └ 3.4679 └ ┘ 1.2359 ⓒ 5.0062 └ ┘ 5.6422 ⓑⓒⓐ
Total	24.3486	28.7355
No.	3	4
Loss in each steel	ⓐ 5.8042 ┌ 1.7701 ┌ ┐ 0.0443 ⓑ 6.1854 └ 3.6203 └ ┘ 1.0931 ⓒ 7.2480 └ ┘ 5.2806 ⓒⓐⓑ	ⓐ 5.9663 ┌ 1.8385 ┌ ┐ 0.0242 ⓑ 4.2500 └ 1.3879 └ ┘ 1.6927 ⓒ 5.4648 └ ┘ 5.4209 ⓐⓒⓑ
Total	31.0460	26.0453
No.	5	6
Loss in each steel	ⓐ 5.4431 ┌ 1.5858 ┌ ┐ 0.0716 ⓑ 7.0925 └ 3.7211 └ ┘ 1.5855 ⓒ 7.0940 └ ┘ 5.4451 ⓒⓑⓐ	ⓐ 5.4188 ┌ 1.6931 ┌ ┐ 0.0242 ⓑ 5.4636 └ 1.3881 └ ┘ 1.8380 ⓒ 4.2521 └ ┘ 5.9683 ⓑⓐⓒ
Total	32.0387	26.0462

Table 3. Total eddy current loss (W/m) in each one of Mode-Adj, listed in descending order.

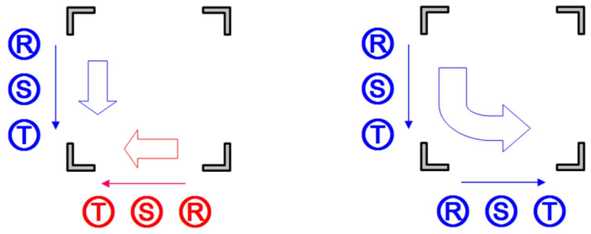
Descending order	A1	A2	A3	A4	A5	A6	avg. value
①	ⓐ ⓑ ⓒ ⓒⓑⓐ 32.0387	ⓑ ⓒ ⓐ ⓐⓒⓑ 32.0387	ⓒ ⓐ ⓑ ⓑⓐⓒ 32.0387	ⓐ ⓒ ⓑ ⓑⓒⓐ 32.0423	ⓒ ⓑ ⓐ ⓐⓑⓒ 32.0423	ⓑ ⓐ ⓒ ⓒⓐⓑ 32.0423	Ⓡ Ⓢ Ⓣ ⓉⓈⓇ 32.0405
②	ⓐ ⓑ ⓒ ⓒⓐⓑ 31.0461	ⓑ ⓒ ⓐ ⓐⓑⓒ 31.0461	ⓒ ⓐ ⓑ ⓑⓒⓐ 31.0461	ⓐ ⓒ ⓑ ⓑⓐⓒ 31.0459	ⓒ ⓑ ⓐ ⓐⓒⓑ 31.0459	ⓑ ⓐ ⓒ ⓒⓑⓐ 31.0459	Ⓡ Ⓢ Ⓣ ⓉⓇⓈ 31.0460
③	ⓐ ⓑ ⓒ ⓑⓒⓐ 28.7354	ⓑ ⓒ ⓐ ⓒⓐⓑ 28.7354	ⓒ ⓐ ⓑ ⓐⓑⓒ 28.7354	ⓐ ⓒ ⓑ ⓒⓑⓐ 28.7354	ⓒ ⓑ ⓐ ⓑⓐⓒ 28.7354	ⓑ ⓐ ⓒ ⓐⓒⓑ 28.7354	Ⓡ Ⓢ Ⓣ ⓈⓉⓇ 28.7354
④	ⓐ ⓑ ⓒ ⓑⓐⓒ 26.0462	ⓑ ⓒ ⓐ ⓒⓑⓐ 26.0462	ⓒ ⓐ ⓑ ⓐⓒⓑ 26.0462	ⓐ ⓒ ⓑ ⓒⓐⓑ 26.0441	ⓒ ⓑ ⓐ ⓑⓒⓐ 26.0441	ⓑ ⓐ ⓒ ⓐⓑⓒ 26.0441	Ⓡ Ⓢ Ⓣ ⓈⓇⓉ 26.0452
⑤	ⓐ ⓑ ⓒ ⓐⓒⓑ 26.0453	ⓑ ⓒ ⓐ ⓑⓐⓒ 26.0453	ⓒ ⓐ ⓑ ⓒⓑⓐ 26.0452	ⓐ ⓒ ⓑ ⓐⓑⓒ 26.0433	ⓒ ⓑ ⓐ ⓒⓐⓑ 26.0433	ⓑ ⓐ ⓒ ⓑⓒⓐ 26.0433	Ⓡ Ⓢ Ⓣ ⓇⓉⓈ 26.0443
⑥	ⓐ ⓑ ⓒ ⓐⓑⓒ 24.3486	ⓑ ⓒ ⓐ ⓑⓒⓐ 24.3486	ⓒ ⓐ ⓑ ⓒⓐⓑ 24.3485	ⓐ ⓒ ⓑ ⓐⓒⓑ 24.3485	ⓒ ⓑ ⓐ ⓒⓑⓐ 24.3485	ⓑ ⓐ ⓒ ⓑⓐⓒ 24.3485	Ⓡ Ⓢ Ⓣ ⓇⓈⓉ 24.3485

Table 4. Loss comparison between Mode-Adj and Mode-Opp.

	Mode-Adj	Mode-Opp
Maximal loss	Ⓡ Ⓢ Ⓣ ⓉⓈⓇ 32.0405 W/m	ⓇⓈⓉ ⓇⓈⓉ 30.2026 W/m
Minimal loss	Ⓡ Ⓢ Ⓣ ⓇⓈⓉ 24.3485 W/m	ⓇⓈⓉ ⓉⓈⓇ 28.2228 W/m

Note: the data of Mode-Opp is collected from Jiang *et al.* [8]

of towers. Moreover, the eddy current losses of steels can be reduced by performing right cable sequencing without any new facilities



(a) (b)

Fig. 7. (Color online) Cables' sequences: (a) anti-sequence and (b) same-sequence.

4. Conclusions

In this study, we have analyzed the electromagnetic field of a power junction tower and calculated the eddy current losses generated in the steels of the tower. A total of 36 cable arrangements of Mode-Adj have been identified and compared. The losses have been compared with those of Mode-Opp. Finally, the best one to reduce eddy current losses in steels of double-circuit junction towers without any new facilities is determined.

The computed results in this study lead to the following conclusions:

- The maximal eddy current loss (32.0405 W/m) in the Mode-Adj group is more than that (30.2026 [8] W/m) in the Mode-Opp group, and the minimal one (24.3485 W/m) of Mode-Adj group is less than that (28.2228 [8] W/m) of Mode-Opp.
- The eddy current loss induced in Rank ① of Mode-Adj with the anti-sequence cable arrangement is the maximum one.
- The minimum eddy current loss is induced in Rank ⑥ of Mode-Adj with the same-sequence cable arrangement.
- The maximum loss is more than the minimum one by 31.59 % (i.e. nearly 1/3).

The results indicate that Mode-Adj configuration with same-sequence cable arrangement is the best choice for reducing the eddy current losses in the steels of the tower. Nowadays, power junction towers have been widely utilized in power systems. Moreover, there are a large quantity of double-circuit junction towers in every modern country. Therefore, the results of this study are helpful for engineer in reducing eddy current loss of junction towers.

List of Symbols and Abbreviations

XLPE	Cross-linked polyethylene
2D	Two-dimensional
Mode-Opp	Mode-Opposite
Mode-Adj	Mode-Adjacent
$\vec{A}$	Z-directional component of the magnetic vector potential (Wb/m, T·m)
$\vec{J}_s$	Density of the excitation source current (A/m^2)
μ	Magnetic permeability (H/m)
σ	Electric conductivity (S/m) or the inverse of electric resistivity (Ω·m)
ω	Angular frequency (rad/s)
Ii	Phase current flowing in conductor (A)
q	Eddy current loss (W/m)
avg.	Average

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