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EDITED BY
Chun Sing Lai,
Brunel University London,
United Kingdom

REVIEWED BY
Vinod Singh Amar,
South Dakota School of Mines and Technology, United States

*CORRESPONDENCE
Yingying Jiao,
yingying.jiao@outlook.com

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Analysis and evaluation of distributed capacitance of multiple cables on secondary circuit

Yucun Qian[1], Bo Yang[1], Kaidi Zeng[1,2], Hao Zhang[1,3], Yingying Jiao[4]*, Xuyong Huang[5], Hui Yu[5], Shaojun Qu[6] and Mengmeng Zhu[5]

[1]Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming, China, [2]Tianjin International Engineering Institute, Tianjin University, Tianjin, China, [3]College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing, China, [4]School of Information and Electrical Engineering, Shandong Jianzhu University, Jinan, China, [5]Electric Power Research Institute, Yunnan Power Grid Co, Ltd., Kunming, China, [6]Honghe Power Supply Bureau, Yunnan Power Grid Co, Ltd., Honghe, China

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Introduction

Due to the increasing number of new energy power generation, the converter station is widely set up at the junction of power generation, transmission, and distribution because it can effectively convert AC and DC (Cui et al., 2021). Therefore, the converter station for the safe and stable operation of the power grid and protection is particularly important. In order to accurately identify and effectively control faults, there are many secondary circuits composed of control cables and relays in converter stations, so the anti-interference ability of secondary circuits is particularly important (Li et al., 2020). Distributed capacitance is a kind of distributed parameter formed by a non-capacitance form. Distributed capacitance is formed between any two insulation conductors with a voltage difference in the circuit, but the size of the distributed capacitance is different. In general, the distributed capacitance is small and has little influence on the circuit, especially in low frequency and short circuits (Wang and Xie, 2018), its influence on the circuit can be ignored. Although the value of distributed capacitance is very small, it sometimes brings interference to the normal work of transmission lines or equipment, especially at high frequencies and long lines (Qiao et al., 2018).

With the increasing application of modern industrial automation technology, it is necessary to centrally control the external electrical equipment, which is bound to increase the length of the control cable (Feng and Song, 2020). The influence of the distributed capacitance between the cable core wires and between the core wires and the shielding layers, especially the distributed capacitance of the control cable, cannot be ignored (Huang and Xu, 2017). In particular, the power of the new relays and contactors is getting smaller and smaller, and the coil impedance is very high. When they are used, the influence of the capacitive current between the cable cores on the AC control circuit is more obvious (Zhang et al., 2018).

In order to solve this problem, many scholars have proposed different methods. For example, this reference (Hou, 2020) proposed reducing the length of the control cable, selecting contactors with small impedance, and selecting contactors with high release voltage to reduce the distributed capacitance, but this is only through common engineering means. Some scholars have also designed an online monitoring system for cable distributed capacitance from the perspective of equipment operation and maintenance, which can realize the early warning of such risks and provide corresponding control measures.

This article will make a brief summary of the existing solutions and methods of modeling, and finally, put forward some suggestions and opinions in this direction. First, in the fault identification caused by distributed capacitance, we can try to use neural networks and other methods for fault prediction and identification. Second, in practical engineering applications, the influence of different materials on the control cable can be tested, so as to select the material with the smallest influence for cable laying.

Analysis of distributed capacitance

The capacitance existing with the distribution of the circuit is called the distributed capacitance (Kang, 2018). For example, there will be a certain capacitance between the adjacent coil turns, between the two discrete components, between the inner core wires of the cable, and between the core wires and the shielding layer (Du and Wan, 2010). Its effect is equivalent to that of a capacitor in parallel to the circuit. The capacitance value of this capacitor is the distributed capacitance. Generally, the distributed capacitance is small without considering its influence, but when the line is long, the distributed capacitance is very large, and its impact must be considered (Liu et al., 2016).

Therefore, it is important to find out the factors that cause distributed capacitance. There are some factors that may lead to distributed capacitance, such as the long-term use of the cable plus perennial moist environment, and with the increase of converter station construction scale, needs more and more complex cable line and length, and the size of the distributed capacitance is proportional to the length of the line. These are the reasons for the distributed capacitance (Wan, 2017).

After understanding the factors affecting the value of distributed capacitance, it is necessary to know what adverse effects the distributed capacitance will have on the power system (Yang, 2022). It is worth learning from the work by Li and Yang (2007) that the measurement circuit, the relay protection circuit, the switch control and signal circuit, the operation power circuit, the circuit breaker, and the electrical locking circuit of the disconnector are all low-voltage circuits, and the secondary equipment is connected to each other. The electrical circuit that monitors, controls, adjusts, and protects the primary equipment is called the secondary circuit. Faults on the secondary circuit often destroy the operation of power production (Ran et al., 2022), and distributed capacitance has a great influence on the secondary circuit and causes secondary circuit fault.

Distributed capacitance has many adverse effects on secondary circuits. We can learn from Zhou (2010) that when the distributed capacitance is too large, it will cause the error of grounding search instrument. Generally, the grounding finder uses the signal injection method to find the grounding fault of a DC system. The signal injection method is divided into the DC method and the AC method. The DC method is to find and locate the grounding fault by injecting a variable DC current into the DC system, which makes the leakage current of the road where the grounding point is located change regularly. However, when the distributed capacitance of the system is too large, the change generated by the DC method will be offset by the distributed capacitance in the charging and discharging process, resulting in the false alarm of the grounding finder.

Luo (2012) introduced that distributed capacitance can cause malfunction of the relay protection switch. When the DC system is in normal operation, the voltage at both ends of the relay coil remains constant. When the grounding fault occurs in the system, the voltage of the positive and negative electrodes to the ground will deviate (Yuan et al., 2019). In the process of change, the relay coil will flow with the current. If the branch distributed capacitance to the ground is small at this time, the current flowing through the capacitance is also small, which is not enough to drive the relay coil to operate (Ma, 2012). If the distributed capacitance of the branch to the ground is large, a large current will be generated, and the current will change with the charging and discharging of the capacitance. According to the charge-discharge characteristics of the capacitor $\tau = RC$, the larger the capacitor is, the longer the charge-discharge time is. Finally, when the current and time meet the relay operating conditions, it will cause relay malfunction, resulting in a series of unnecessary losses (Ren and Hu, 1989).

Therefore, Wu and Yan (2007) introduced that modeling and analyzing distributed capacitance is of great significance to eliminate its adverse effects. Generally, there is distributed capacitance between the wire core and the wire core inside the cable, as well as between the wire core and the shielding layer. Assuming that the two conductors have the same amount of heterogeneous charge when the two conductors have voltage, the capacitance C will be generated inside them (Zhang et al., 2008). For the plate, as shown in the following formula:

$$C = \frac{\varepsilon S}{4\pi k d} \tag{1}$$

where ε is the dielectric constant of the insulator between two conductors, S is the plate area, d is the distance between plates, and k is the static constant.

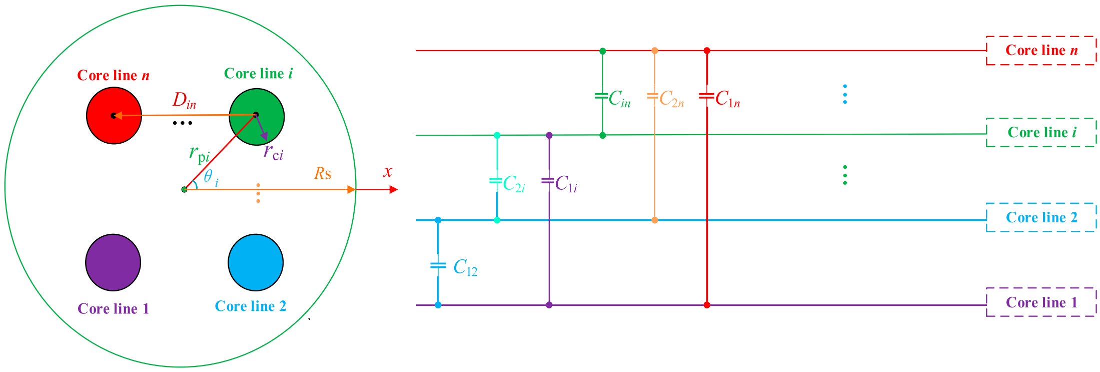

FIGURE 1
Distributed capacitance model of *n*-core cable.

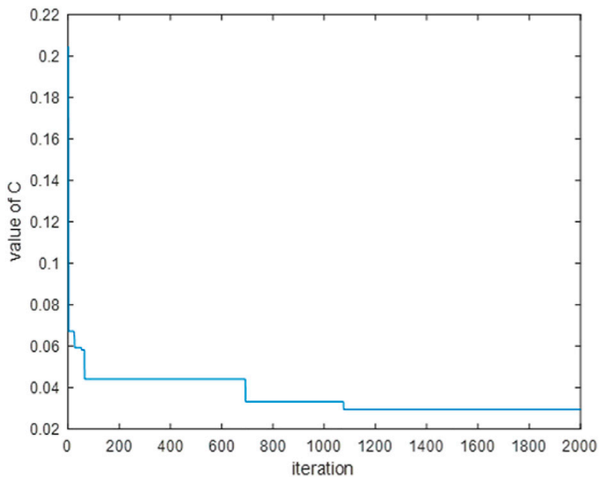

FIGURE 2
Convergence curve of four-core cable lines.

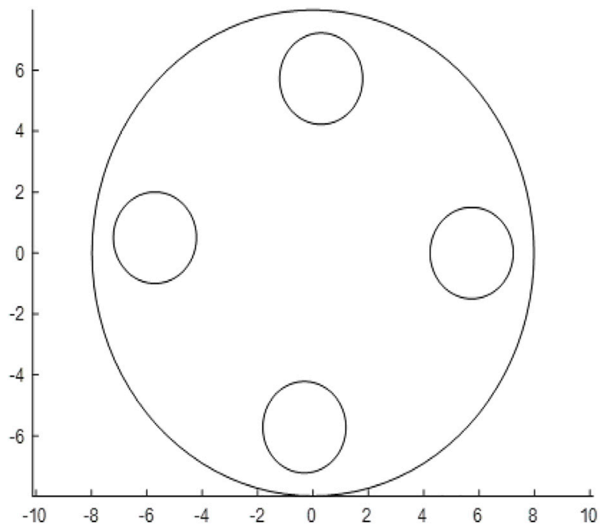

FIGURE 3
Optimal topology of four-core cable lines.

If the conductor in the multi-core cable is regarded as a plate, the capacitance between the conductors is distributed capacitance. The distributed capacitance formed by the multi-core cable is equivalent to the capacitance between the plates, as follows in Figure 1.

First, the capacitance relationship between the core wires can be determined as follows:

$$C_{ij} = \frac{0.01207l}{\lg D_{ij}/r_{ci}} \tag{2}$$

where C_{ij} represents the stray capacitance between the *i*-th and *j*-th cable cores; l represents the length of each cable core; D_{ij} represents the distance between the *i*-th and *j*-th cable core axes; r_{ci} represents the radius of *i*-th cable core.

Since the cross-sectional area of a cable is fixed and the cable radius R_s of the cable is fixed, it can be seen from the formula that the radius r_{pi} of the single-core wire should meet the following conditions:

$$0 < r_{pi} < R_s - 1.5 \times r_{ci} \tag{3}$$

where r_{pi} represents the pole diameter of *i*-th cable core axis in the model; r_{ci} represents the radius of *i*-th cable core; R_s represents the cable radius.

Therefore, this article takes the position polar coordinate form of the core line (r_{pi}, θ_i) as a variable and the minimum capacitance of all core lines as the objective function of this article. At the same time, the radius r_{pi} of a single core line is taken as the constraint condition of this article, which can be shown as follows:

$$D_{ij} = \sqrt{r_{pi}^2 + r_{pj}^2 - 2r_{pi}r_{pj}\cos(\theta_i - \theta_j)} \quad (4)$$

Objective function:

$$C_{ij} = f(r_{pi}, \theta_i) = \min\left(\frac{0.01207l}{\lg D_{ij}/r_{ci}}\right) \quad (5)$$

Constrain condition:

$$0 < r_{pi} < R_s - r_{ci} \quad (6)$$

In practical application, the secondary loop cable is very long, and it is difficult to measure its transmission parameters. Therefore, the transmission parameters of the cable are obtained by the analytical method and electromagnetic field numerical calculation. The transmission line with secondary cable equivalent is regarded as a two-port network.

According to the transmission line theory, the transmission parameter matrix of the two-port can be obtained as follows:

$$T_2 = \begin{pmatrix} A_2 & B_2 \\ C_2 & D_2 \end{pmatrix} = \begin{pmatrix} \cosh(\gamma l) & Z_C \sinh(\gamma l) \\ \frac{1}{Z_C}\sinh(\gamma l) & \cosh(\gamma l) \end{pmatrix} \quad (7)$$

$$Z_C = \sqrt{(R_0 + sL_0)/(G_0 + sC_0)} \quad (8)$$

$$\gamma = \sqrt{(R_0 + sL_0) * (G_0 + sC_0)} \quad (9)$$

where Z_C is the wave impedance of the transmission circuit, γ is the propagation parameter of the transmission line, l is the length of the transmission line, L_0, C_0, G_0, R_0, are inductance, capacitance, conductance, and resistance per unit length of the transmission line.

Processing of distributed capacitance

When the value of distributed capacitance is too large, it will cause harm to the power system (Liu and Wan, 2017). Therefore, it is necessary to know what factors affect the value of distributed capacitance and how to reduce it. The factors affecting the value of distributed capacitance are introduced in the work by Luo (2021).

Length of transmission cable is important. The longer the cable, the larger of distributed capacitance. The more the cores, the greater the distributed capacitance. Different dielectric constants of different insulators result in different values of distributed capacitance. The screen cable is smaller than the non-screen cable. Contrary cable is less than non-contrary cable.

Reducing the value of distributed capacitance is very necessary to maintain the stable operation of the system. Below are some methods of reducing the influence of distributed capacitance.

(a) Reducing the length of the control cable. In the process of system design, it is necessary to shorten the length of the secondary cable as much as possible. For some common cables, the length should be shorter so as to control the adverse effect caused by the distributed capacitance (Zhang et al., 2017).
(b) Select relay with high release voltage. When the cable construction is completed, the cable length from the control room to the primary equipment is determined, which is basically impossible to change, so it is very difficult to change the value of the distributed capacitance of the cable. Another effective preventive measure is to improve the operation voltage value of the relay so as to avoid misoperation of the relay. If the intermediate relay with high operation voltage and fast operation can be selected, safety and sensitivity can be ensured (Zhang et al., 2017).
(c) Application of multi-core cable grounding. Multi-core shielded control cable is composed of several copper core wires twisted together, and then wrapped with a shielding layer, which can effectively avoid interference voltage affecting the normal operation of relay equipment (Ji, 2016).

In addition, in Ji (2016), the author analyzes the current of the circuit by establishing the circuit model of the relay and combining the action current of the relay. Then, according to the corresponding formula of distributed capacitance and distance, the corresponding cable length is calculated, so as to judge that when the cable length exceeds the value, the wrong action of the relay will be caused.

In addition to the method of reducing distributed capacitance in practical engineering, Song et al. (2017) specially designed an online monitoring system for cable distributed capacitance from the perspective of equipment operation and maintenance, which realized the early warning of such risks and provided corresponding control measures. By injecting a low-frequency AC signal into the DC system, the monitoring system calculates the distributed capacitance with AC current as the measurement quantity and compares it with the critical value. In order to realize the steady and accurate measurement of distributed capacitance, a current transformer is designed based on the principles of magnetic saturation and magnetic flux induction. Using constant resistance mode in DC electronic load, a voltage balancing module is designed to balance DC bus voltage.

For the influence of the distributed capacitance of the line applied to the protection device, Yang et al. (2022) directly changed the construction idea of the longitudinal protection, so that the protection device can be free from the influence of the distributed capacitance. It is based on the analysis of the voltage polarity characteristics of the current-limiting reactor on both sides of the line when the fault occurs inside and outside the region, and the Kendall correlation coefficient is used to construct the fault identification criterion. Then, the ratio feature of the sum of the low-frequency transient energy of the bipolar reactance voltage is extracted by the variational mode decomposition algorithm to realize the fault pole selection function, and a longitudinal protection scheme based on the current-limiting reactance voltage is proposed. Nowadays, flexible DC transmission technology has developed rapidly.

Zhang et al. (2022) constructed transmission line protection using this technology to remove the influence of distributed capacitance and proposed a longitudinal protection scheme based on low-frequency reactive direction. This article first analyzes the frequency characteristics of the distributed capacitance current of the line and proposes to use low-frequency reactive power to describe the flow law of the distributed capacitance current. Then, the difference of low-frequency reactive power direction between inside and outside is analyzed, and the fault identification criterion is constructed.

Discussion and conclusion

In general, the size of the distributed capacitance has a very important influence on the secondary circuit of the converter station. When the cable line is long and the distributed capacitance between the cable cores is large, the decrease in the capacitive reactance will cause the relay to malfunction or refuse to act, resulting in abnormal control or greater fault. A number of solutions are mentioned earlier, such as reforming circuits, shortening cable lines, and selecting cables with smaller distributed capacitances.

In the model established in this article, the distributed capacitance of the secondary loop is reduced by optimizing the arrangement of the core wires of the secondary loop cable. Taking the four-core cable as an example, the marine predators algorithm (MPA) is used in the optimization model. MPA is a novel heuristic algorithm, which uses three stages to describe the process of marine predators. It originates from the theory of marine survival; marine predators choose the best foraging strategy between Levy walking and Brownian motion so as to realize the optimization of the algorithm (Hu and Cui, 2021). The optimization results are obtained as follows through MATLAB simulation.

The simulation results show that the simulation model has a fast convergence speed, can optimize the cable core configuration, and reduce the size of distributed capacitance. Simulation results are shown in Figures 2, 3. Because the parameters of general cables have relevant national standards, in the model, the radius of the cable core is constrained within a certain range, and the heuristic algorithm is used to search and iterate continuously to obtain the minimum distributed capacitance and the optimal topology of the core layout.

Some scholars have also designed real-time detection and prediction of distributed capacitance to protect and prevent it in advance. Some scholars also have a way to avoid the influence of distributed capacitance by directly changing the design of protection. On the basis of these scholars, this article also puts forward the future development direction of such problems. Nowadays, there are many fault identifications, weather load forecasting, and so on. We can also use neural network, deep learning, and heuristic algorithm to construct the prediction and identification of distributed capacitance, which can effectively reduce or predict the probability of fault occurrence in advance, so as to avoid the faults caused by distributed capacitance. In the selection of materials, you can continuously improve and test the cable core used so as to select the materials that cause the smallest distributed capacitance or have the smallest impact on the secondary circuit.

Author Contributions

YQ: writing the original draft and editing. BY, KZ, XH, and HY: conceptualization. HZ, YJ, SQ, and MZ: visualization and contributed to the discussion of the topic.

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Conflict of Interest

Authors XH, HY, and MZ were employed in the Electric Power Research Institute of Yunnan Power Grid Co., Ltd. Author SQ was employed in Honghe Power Supply Bureau, Yunnan Power Grid Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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