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Inductance calculation of submarine DC transmission line based on finite element analysis

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Abstract: [**Objectives**] Because of the characteristics of submarine Direct Current (DC) transmission cables, traditional circuit inductance calculation methods are unable to fit the system. There is a big error between the calculating value and the actual value. This paper studies the finite element method to reduce the calculation error. [**Methods**] The applicability of common line inductance calculation formulas to submarine DC system is discussed firstly. Then a short-circuit experimental system is set up. The inductance of circuit in the system is measured, and a simulation model of the experimental system is established. For a comparing purpose, the total inductance of the line is calculated by finite element analysis in the ANSYS/Maxwell software too. With the inductance values, the equivalent circuit model of the experimental system is simulated in the Matlab/Simulink software. The simulation waveforms of the short-circuit current and the measured waveform are analyzed and compared. [**Results**] The result shows that the finite element analysis method is able to improve the accuracy of calculation of submarine DC transmission line equivalent inductance, and reduce the error in DC power system transient analysis. [**Conclusions**] The achievement can provide support for further simulation model development and calculation method research.

Key words: submarine; DC transmission; loop inductance; Finite Element Analysis (FEA)

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0 Introduction

The submarine Direct Current (DC) transmission network has such characteristics as low voltage, short line and simple network structure. The voltage level of the network is usually not higher than DC 1 000 V and the length of the transmission cables is usually not more than 1 km, which is a tree-structure grid structure. The calculation parameters of the transmission lines are mainly electrical resistance under normal operating conditions. However, in the short-circuit fault analysis of the power grid, the electromagnetic characteristics of transmission lines have great influence on the short-circuit current, so the inductance of the lines cannot be ignored. At present, the research on the power supply and load of the submarine DC grid is more [1-3], and research on the line cables is mainly focused on the electromagnetic interference under AC/DC hybrid power supply [4-5], but the calculation of the inductance parameters of transmission cables is less. In the design of the submarine DC grid, the calculation of inductance is usually conducted according to the cable parameters in the cable manual provided by the manufacturer. However, the actual inductance parameters of the DC transmission lines are influenced by the loop formed by the line, the laying environment of the cable, the cable spacing and so on. In different environments, the actual inductance value of lines is greatly different from that calculated by the traditional method. The inductance value of the transmission lines will affect the calculation of the transient characteristic of the system, and then affect the corresponding design index. In recent years, many papers

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have been published to analyze the transmission line model and parameter calculation method in the multi-terminal DC transmission grid in onshore grid. Dong et al. [6] studied the positive sequence of cables under different return paths, return lines and metal sheaths, especially the calculation method of zero-sequence impedance, which improved the accuracy of parameter calculation of high voltage cables. Akkari et al. [7] discussed the different effects of using different equivalent circuit models of DC cables to analyze the characteristics of the onshore high voltage DC grid. Du et al. [8] proposed a fast calculation method for the mutual resistance of the high speed railway track circuit, which took the earth influence into account, and got better calculation results. Compared with the power grid objects in the above studies, the DC voltage level in the submarine DC grid is lower, the DC current across the cables is huge, and the cables are arranged more closely in the finite space of the submarine. Therefore, it is necessary to analyze the applicability of the existing methods to calculate the inductance parameters of submarine DC transmission line.

This paper will first elaborate the laying characteristics of submarine DC transmission cables, discuss the applicability of common line inductance calculation equations to submarine DC transmission line, establish a transmission line model of short-circuit experimental system of submarine DC grid in ANSYS/Maxwell software and calculate the total inductance value of the transmission lines using the Finite Eelement Analysis (FEA) method. Then, Matlab/Simulink software is used to simulate the experimental system. The waveforms of the short-circuit current obtained from the simulation are compared with the measured waveforms to analyze the effect of the equivalent inductance value obtained by different inductance calculation methods on the short-circuit current waveforms of the system.

1 Laying state of submarine DC transmission line

Due to the small space, the submarine usually lays multiple transmission cables in a compact arrangement and designs the cable guide plates to fix the position of the cables. The guide plate of the cables is shown in Fig.1 (relative permeability of the material is close to 1) and the cable spacing is relatively smaller compared with the cable conductor radius. Besides, the structure, laying and use pattern of cable should also be fully considered when calculating the transmission line inductance.

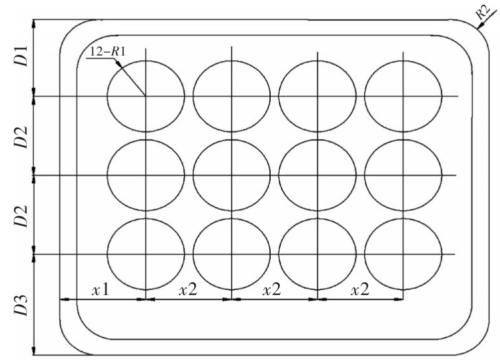


Fig.1 Scheme of cable guiding plate

2 Inductance analysis of submarine DC transmission line

2.1 Equivalent inductance of loop

It is known from Reference [9] that if current I is applied to a loop, the ratio of the flux linkage ψ established by the current and crosslinking the loop to the current I is called the self-inductance coefficient of the loop (referred to as self-inductance) and expressed as L, namely:

$$L=\frac{\psi}{I} \tag{1}$$

It can be seen from Eq. (1) that inductance is formed by a loop where I is the current in the loop and ψ is the flux linkage in the area enclosed by the loop.

When analyzing and calculating the power system, it is usually necessary to establish an equivalent circuit model of the system. In the circuit [10], the inductance element is a set of coils, which reflects the physical phenomenon that the current generates magnetic flux and magnetic field energy storage. Its element characteristics are shown in the algebraic relationship between flux linkage ψ and current I:

$$\psi=LI \tag{2}$$

It is easy to confuse equivalent inductance of loop and inductance components. For inductance components, the inductance value is certain, while the equivalent loop inductance is determined by the loop. In the cable design manual, the manufacturer usually provides a 50 Hz inductance value. However, the test environment of the inductance value is far from the actual laying environment of the submarine transmission cable, that is, the loops formed are not the same, and the total inductance of loop is under the influence of the integrated environment such as distance among cables and cable radius. So when the short-circuit current is calculated using the inductance value per unit length in the cable nameplate value, it will easily lead to large errors.

2.2 Applicability analysis of commonly-used inductance calculation equations

2.2.1 Calculation of internal self-inductance and external self-inductance

According to the definition of inductance, the equation is as follows[9]:

$$L = L_i + L_e \tag{3}$$

where L_i is the internal self-inductance, which is equal to the ratio of the flux linkage that crosslinks part of the current of the wire to the current of the wire; L_e is the external self-inductance, which is equal to the ratio of the flux linkage that crosslinks all the current of the wire to the wire current. The internal self-inductance and external self-inductance calculation equations can be obtained respectively by integrating the flux linkage in the magnetic field using the Biot-Savart's law:

$$L_i = \frac{\mu_0}{8\pi} l \tag{4}$$

$$L_e = \frac{\mu_0}{2\pi} (\ln \frac{r_2}{r_1}) l \tag{5}$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the vacuum permeability; r_1 is the core radius; r_2 is the radius of the outer conductor circle; and l is the length of the cable.

When calculating the total inductance of the loop by solving the internal self-inductance and external self-inductance respectively through the traditional calculation method, it can be accurately calculated only when it is possible to distinguish the inner and outer flux linkages, i.e., the inner and outer flux linkages do not overlap. When the traditional method is used to calculate the inductance of the long, straight and parallel doublewires, the smaller the ratio of the distance between the wires to the wire radius is, the greater the calculation error is.

2.2.2 Calculation of per unit self-inductance of a single cylindrical long wire

In power system analysis[11], the inductance calculation equation for a single cylindrical long wire is:

$$L = \frac{\mu_0}{2\pi} (\ln \frac{2l}{D_s} - 1) \tag{6}$$

where $D_s = r_1 e^{-\frac{1}{4}}$ is the geometric mean distance of the cylindrical wire. Eq. (6) is applicable to the analysis of onshore power transmission network where the length of the wire is much longer than the distance between the wires. The value of the external self-inductance is greater than that of the internal self-inductance, so the internal self-inductance can be ignored under this circumstance. When calculating the external self-inductance, the center point of the transmission lines of the three-phase four-wire power system is grounded, and it can be considered that the single wire and the earth at infinity form a loop.

2.3 Analysis of the inductance value of submarine transmission line

Two types of power cables are commonly used in submarines: unshielded cables and shielded cables, whose structures are shown in Fig.2 and Fig.3 respectively. The use pattern of cables is also different: for unshielded cables, one cable conductor is required to connect to the positive pole of the power supply and another one is connected to the negative pole to form a loop; for shielded cables, a loop can be formed by the conductor and shielded layer (Fig.4) or through the conductors of two cables (Fig.5).

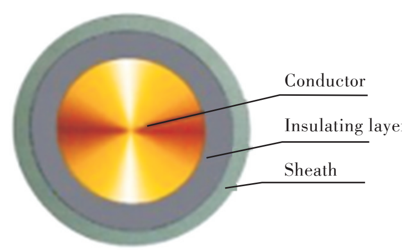


Fig.2 Structure of unshielded cable

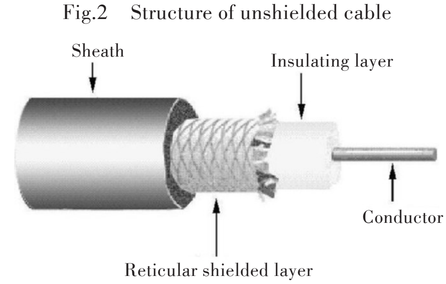


Fig.3 Structure of shielded cable

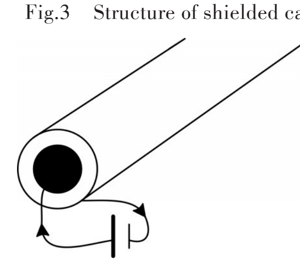


Fig.4 Loop of wire with skin

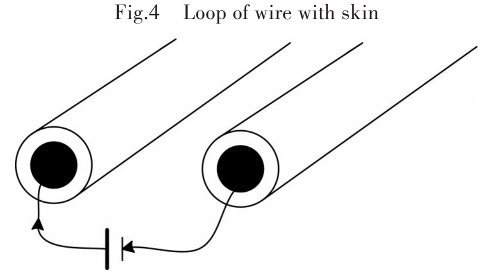


Fig.5 Loop of two wires

When a cable is used as shown in Fig. 4, the conductor and the shielded layer are connected to the positive and negative poles of the power supply respectively. The area surrounded by the loop is entirely inside the cable, the generated magnetic field is concentrated in the cable and the external magnetic field of the cable is 0. When multiple shielded cables are connected in parallel using this loop connection method, the magnetic field generated by each cable does not affect each other. Supposing that the cable impedance of a transmission line is X_1, when the number of transmission line cables increases from 1 to n, the equivalent line impedance is X_n. Because there is no electromagnetic crosstalk among the various cables, there is a linear relationship: $X_n = \frac{1}{n} X_1$.

When the cable is used as shown in Fig. 5, the shielded cable does not form a loop by itself and the magnetic field covered area between positive and negative lines is not only in the cable, but also in the space outside the cable. The magnetic fields generated by multiple loops are coupled to each other, so there is no linear relationship between the total inductance of transmission line formed by multiple cables in parallel and the inductance of a single cable, namely, $X_n \neq \frac{1}{n} X_1$. In low-frequency magnetic field analysis, since the current in the shielded cable flows only in the wire, the loop inductance calculation of shielded cable is not different from that of the ordinary cables or unshielded conductors.

3 Calculation of inductance based on FEA

3.1 Calculation principle

The FEA theory is to use finite unknown values to approximate a real system with infinite unknown values and replace complicated problems with simple ones to get answers. At present, FEA has been extensively applied to the analysis and calculation of field domain and good results have been achieved. ANSYS/Maxwell is one of the widely used low-frequency electromagnetic field finite element software, which has been widely used in the engineering electromagnetic field [12-13]. In the parameter calculation, ANSYS/Maxwell software uses magnetic field energy. The relationship between magnetic field energy, inductance and current is:

$$W_m = \frac{1}{2} L_{total} I_{total}^2 \tag{7}$$

where W_m is the magnetic field energy; L_{total} is the total loop inductance; and I_{total} is the total loop current.

According to the total loop energy value calculated by software, the total loop inductance is

$$L_{total} = \frac{2W_m}{I_{total}^2} \tag{8}$$

Energy is obtained by integrating the magnetic field over the entire field domain:

$$W_m = \frac{1}{2} \int_V H \cdot B \mathrm{d}V \tag{9}$$

where H is the magnetic field strength; B is the magnetic induction intensity; and V is the impedance of the cable.

3.2 Establishment of model

The experimental system adopts a certain type of battery and DC power cable (JYJPJ85SC-1) for submarines. According to the actual laying of the cables in submarines, the cable guide plate is designed to fix the position of the cables in the experimental system and the positive and negative cable ends are directly connected to a switch. A short-circuit fault is simulated by closing the switch. The experimental system is shown in Fig. 6.

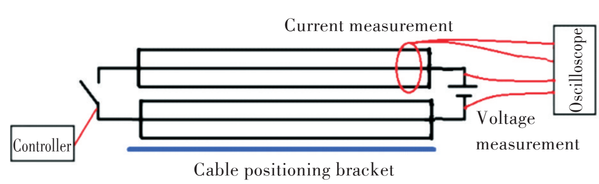


Fig.6 Schematic diagram of experimental system

The impedance nameplate value of the transmission cable in the experimental system is $Z = 0.062 + \mathrm{j}\,0.083\,7$ Ω/km (50 Hz) and the average length of the cable group is 16.7 m. The cable line is shown in Fig. 7. The line is composed of 6 cables, 3 of which are connected in parallel to the positive pole of the power supply and the other 3 are connected to the negative pole to form three loops. The structure of the cable guide plate is shown in Fig. 8 where "+" indicates that the cable through the hole is connected to the positive pole of the battery and "-" indicates that the cable through the hole is connected to the negative pole.

The cable model is established in ANSYS/Maxwell software. The flowchart is shown in Fig. 9.

Fig. 10 shows the cable model, in which Fig. 10(a) is the overall diagram of the model, and Fig. 10(b) is the partial enlarged view of the finite element meshes. Fig. 11 shows the magnetic field distribution of the transmission line obtained by FEA method. It

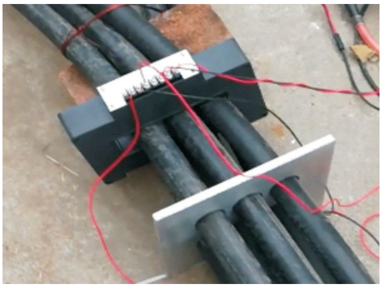


Fig.7 Transmission cable in experimental system

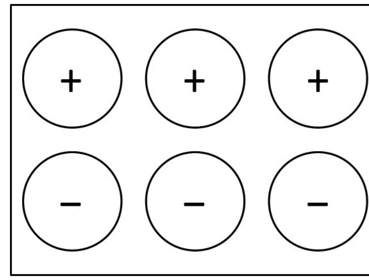


Fig.8 Schematic diagram of cable guide plate of experimental system

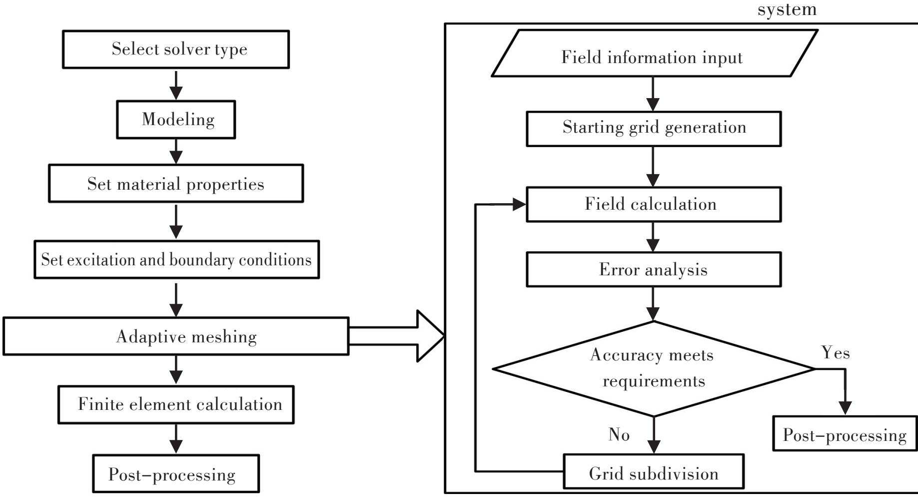
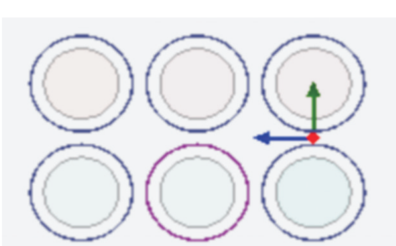


Fig.9 Modeling flowchart

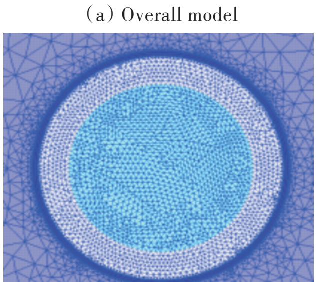
can be seen from the above that the magnetic field generated by each loop is severely coupled, the shape of the magnetic circuit is relatively complex, and the total magnetic field energy is concentrated in the area surrounded by the loop.

3.3 Comparative analysis of calculated and measured results of inductance

For the transmission lines of the experimental system, the total loop inductance data as shown in Table 1 are obtained through finite element calculations and physical measurements. Fig. 12 shows the characteristic curve of the total inductance of the loop as a function of frequency, reflecting that the total loop inductance gradually decreases as the frequency of the

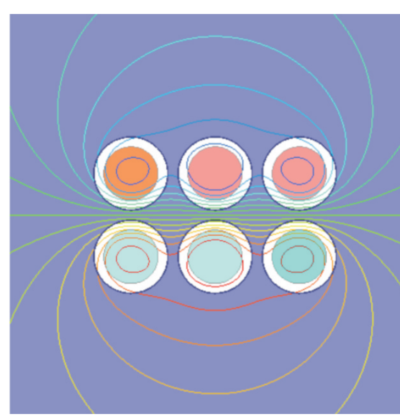


(a) Overall model

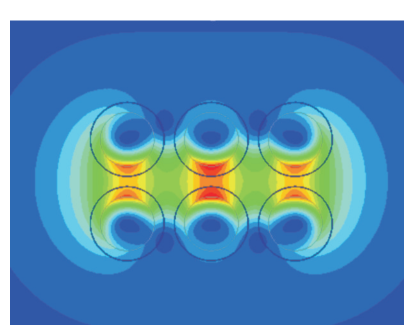


(b) Partial enlarged view of the finite element meshes

Fig.10 Maxwell model



(a) Magnetic induction line



(b) Cloud chart of magnetic induction density

Fig.11 Magnetic field diagram of experimental cable array excitation (current) increases and finally tends to be stable.

Table 1 Inductance values

Frequency/Hz	Measured value/μH	Calculated value/μH	Error/%
0	4.51	4.27	5.5
50	4.39	4.13	6.2
100	4.01	3.89	3.0
1 000	3.37	3.26	3.5
10 000	3.22	3.04	5.9
20 000	3.16	3.01	4.9

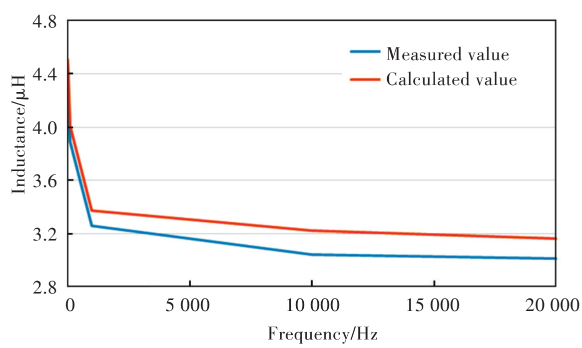


Fig.12 The variation of total inductance with frequency

If the coupling among cables is ignored and when the cable nameplate value is 50 Hz, the total loop inductance is 1.48 μH. From Table 1 and Fig. 12, it can be seen that the total loop inductance obtained by using finite element calculation and actual measurement is almost 2 times higher than the calculated total loop inductance according to a given nameplate value of cable, indicating that the state of laying of the actual submarine makes the coupling among the parallel loops very serious.

4 Analysis of influence of calculated line inductance on short-circuit current of submarine DC system

In the experimental process, the signal waveform of short-circuit current is measured by the Hall probe, and the curve is shown in the oscilloscope as shown in Fig. 13. After the data in the oscilloscope are exported, the waveform as shown in curve ① in Fig. 14 is obtained.

In the Matlab/Simulink software, the short-circuit fault status of the experimental system is modeled and simulated, in which the storage battery is simulated by the series self-resistance and self-inductance of power supply, and the series inductance of resistors is used for line modeling. The obtained simulation waveform of short-circuit current is compared with the measured waveform, and then the

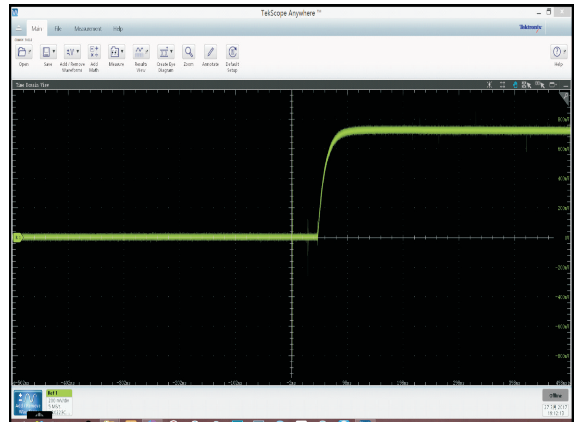


Fig.13 Short circuit current measuring waveform

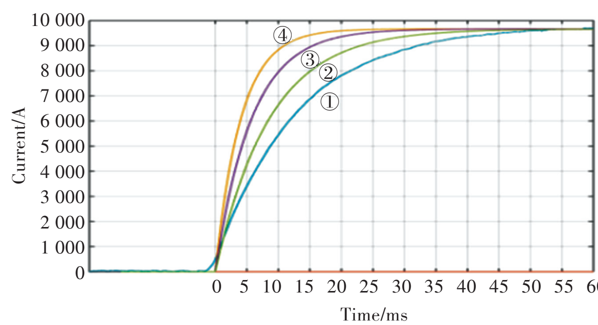


Fig.14 Comparison of short circuit current waveforms

comparison of short-circuit current waveforms as shown in Fig. 14 is obtained. In Fig. 14, Curve ① shows the measured short-circuit current waveform of the experimental system; Curve ② shows the short-circuit current waveform obtained by calculating the total impedance of the transmission line using the FEA method; Curve ③ shows the short-circuit current waveform obtained from the cable nameplate value of the transmission line; Curve 4 shows the short-circuit current waveform obtained from the pure resistance simulation where the inductance of the DC transmission line is neglected.

It can be seen from Fig. 14 that all the 4 short-circuit current curves have a transient process and finally reach a steady-state value. The time constant of short-circuit current waveform of actual system is 12.6 ms and reaches the maximum value after 0.5 s. When T=10 ms, I_1=5 489 A, I_2=6 532 A, I_3=7 988 A, and I_4=8 900 A. In the transient calculation of the DC system, the instantaneous switching capability needs to be capable of cutting off the 8 900 A current at 10 ms if the influence of the line inductance is completely ignored. However, in the actual system, the short-circuit current at this time can only reach 5 489 A. Therefore, the use of improper inductance value would cause the calculated value of the short-circuit current to be too large, thereby increasing the difficulty of designing the protection system.

It can also be seen from Fig. 14 that the calculated inductance value is more accurate and closer to that in the actual system when finite element method is used.

5 Conclusions

In this paper, a short-circuit experimental system of a real submarine is set up to simulate the short-circuit fault of submarine DC power system, the parameters of the testing cables are measured, and a simulation model of the transmission line is established. Besides, the line inductance is calculated using the finite element method, and experimental waveforms and simulation waveforms are compared and analyzed. The main research findings are as follows:

1) Because the arrangement space of submarine DC main grid is compact and there are strong couplings among various transmission loops, the calculation method of equivalent inductance of transmission lines using the earth to form a loop and ignoring the electromagnetic influence among the wires in the onshore grid is not applicable.

2) Establishing a model based on the laying of the actual submarine cables and using FEA method to calculate the equivalent total inductance of the lines can effectively improve the accuracy of calculating the equivalent total inductance of submarine DC transmission lines, and better adapt to the transient calculation requirements of the submarine DC grid, thus reducing the errors in the transient analysis of the DC grid.

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舰艇对空中来袭目标意图的预判方法

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摘　要:[**目的**] 为使舰艇能在短时间内正确预判空中来袭目标的意图,提出应用异质集成学习器解决该模糊不确定性分类问题。[**方法**] 首先选取极限学习机、决策树、Skohonen神经网络和学习矢量化(LVQ)神经网络4种子学习器,使用集成学习结合策略构建异质集成学习器;然后利用该集成学习器训练测试训练集100次,得到该分类实验平均准确率和计算时间。为提高准确率,进行了集成修剪,剔除"劣质"的LVQ神经网络,重新构建效率更高的异质集成学习器,其实验结果具有极高的精度,但计算耗时长。为此,提出对Skohonen神经网络子分类器做"线下训练、线上调用"的改进。[**结果**] 仿真实验表明,从探测到空中目标到预判出各来袭目标意图总用时为4.972 s,预判精度为99.93%,很好地满足了精度和实时性要求。[**结论**] 该研究为作战决策提供了一种新颖而有效的方法,同时也为小样本分类识别问题提供了一种较好的实现途径。
关键词:集成学习; 极限学习机; 决策树; Skohonen神经网络; LVQ神经网络; 集成修剪

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基于有限元分析的潜艇直流输电线路电感计算

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摘　要:[**目的**] 潜艇直流电网的输电电缆敷设特殊,传统的线路电感计算方法得到的数值与实际系统中的电感值之间存在较大误差,为了减小计算误差,研究采用有限元分析法计算输电线路电感值。[**方法**] 阐述潜艇直流输电电缆的特点,讨论常用线路电感计算公式在潜艇直流输电线路电感计算中的适用性。搭建实艇短路模拟物理实验系统,测量实验系统线路电感参数,同时在ANSYS/Maxwell软件中采用有限元法计算电感值。在Matlab/Simulink软件中仿真试验系统,依据计算电感值建立等效电路模型,对比分析短路电流仿真波形和实测波形。[**结果**] 研究结果表明,采用有限元分析法能够有效提高潜艇直流输电线路等效总电感值计算精度,更好地适应潜艇直流电网的暂态计算需求。[**结论**] 可为后续仿真模型开发、算法研究提供支持。
关键词: 潜艇; 直流输电; 回路电感; 有限元分析