Study on electric field induction energy extraction of distribution lines based on pulse power technology

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ABSTRACT

With the development of power system automation, the way of replacing manual line inspection with unmanned equipment is rising day by day. Inductive energy extraction technology is installed on the low-voltage side of the tower, and energy is extracted by the changing electric field near the inductive transmission line. When the line works, the electric field is stable and the power supply is relatively stable, so it is a good choice for online monitoring system with low power consumption and periodic operation. The main formation mechanism of induced overvoltage in distribution lines is that discharge channels will be formed in the process of discharge, and electromagnetic fields will be formed in the surrounding space, which will lead to induced overvoltage in distribution lines with surrounding power grids. Therefore, based on pulse power technology, this paper further studies the electric field induced energy extraction of distribution lines, and the simulation results show that the simulation results of finite element software are basically consistent with the experimental values, no matter whether the plate size or voltage changes, so we can know that the simulation results of the method proposed in this paper are desirable. However, the initial permeability is low, which is suitable for energy extraction at high current. Permalloy has a high initial permeability, but it is easy to saturate when the current is slightly larger.

Keywords: Pulse power technology; Distribution line; Electric field induction energy extraction

1. INTRODUCTION

With the intelligent construction of the power system, the online monitoring equipment gradually replaces the manual patrol inspection. However, due to the high voltage level of the line installed on the outdoor tower, the power supply design cannot directly use the line power supply. In order to reduce the maintenance cycle of the equipment, the self-contained power supply is often used. Distribution line branches are mostly distributed with high density and low insulation level, and are highly sensitive to induced overvoltage. The distribution network fault rate caused by lightning strikes accounts for more than 70% of the total fault rate. The main formation mechanism of the induced overvoltage of the distribution line is that the lightning will form a discharge channel during the release process, and the surrounding space will form a discharge magnetic field, resulting in the induced overvoltage phenomenon of the distribution line with the surrounding power grid [1]. Regular inspection and maintenance of transmission and transformation system is an important means for power grid operation department to ensure transmission safety.

With the development of power system automation, the way of replacing manual line patrol with unmanned equipment is increasingly emerging. The induction energy extraction technology is installed at the low voltage side of the tower, and the energy is extracted by changing the electric field near the induction transmission line. The electric field is stable when the line works, and the power supply is relatively stable. It is a good choice for the power supply of the online monitoring system with low power consumption cycle operation [2]. However, due to the limitation of the onboard battery capacity, the rotorcraft UAV cannot carry out long and long distance autonomous patrol inspection, or needs human intervention during its long and long distance patrol inspection. In this paper, based on the pulse power technology, the electric field induction energy extraction of distribution lines has been further studied. The pulse power technology has officially developed as an independent department in recent years. In fact, pulsed discharge, as the basis of pulsed power technology, has long existed in nature. The study of pulse discharge begins with the study of natural lightning characteristics, as well as its harm to transmission lines and buildings and its protective measures. At that time, the discharge was limited to millisecond and microsecond.

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Due to the large fluctuation range of high voltage bus current, it is required that the power supply can adapt to a wide range of current variation. If the standby power supply is not added, the power supply can only be powered in the range of tens of amperes to thousands of amperes, with a large dead band. For this reason, a design scheme of induction power supply based on pulse power technology is proposed. Taking the development of microwave and laser as an example, it is impossible to generate high-power and high-efficiency millimeter or submillimeter microwave by using the principles of klystron and traveling wave tube; It is also impossible to generate high-power, high-efficiency and wavelength adjustable laser beams by general methods [3-4]. While people are exploring and looking for new solutions, they find that pulse power technology is a good way to solve these problems, with a wide current working range, and it has been verified by simulation and experiment.

2. DESIGN OF PULSE POWER ELECTRIC FIELD INDUCTION ENERGY EXTRACTION

2.1 Principle of energy extraction by pulsed power electric field induction

The main content of pulse power technology research is how to store energy economically and reliably, and transmit large energy and large power to the load effectively. The ever-increasing requirements of energy, power, rise time, flatness, repetition rate, stability and life have put forward a series of scientific and technical problems for pulse power technology. Under the high-voltage AC line, there will be four different kinds of sensed electricity for the stopped conductor, namely electromagnetic induced voltage, induced current, electrostatic induced voltage and current. The types of induced electricity generated are different with different states of outage lines [5]. In the actual measurement of lightning induced overvoltage phenomenon in distribution lines, due to the limitation of technical conditions, only the return lightning current waveform at the bottom of lightning channel can be measured.

At present, the commonly used power supply mode of monitoring devices is mainly to convert intermittent energy such as solar energy and wind-solar complementary energy into continuous power supply through energy storage components such as batteries and supercapacitors. In the engineering calculation model of lightning current waveform, the calculation of time and space distribution of return lightning current is based on the lightning current at the bottom of lightning channel [6-7]. The energy extraction by electric field induction of pulsed power needs to go through four processes: inductive energy storage from electric field, pulse shaping, high-frequency oscillation and mutual inductance output, as shown in Figure 1, in which pulse shaping is the process of development and suppression of air gap discharge.

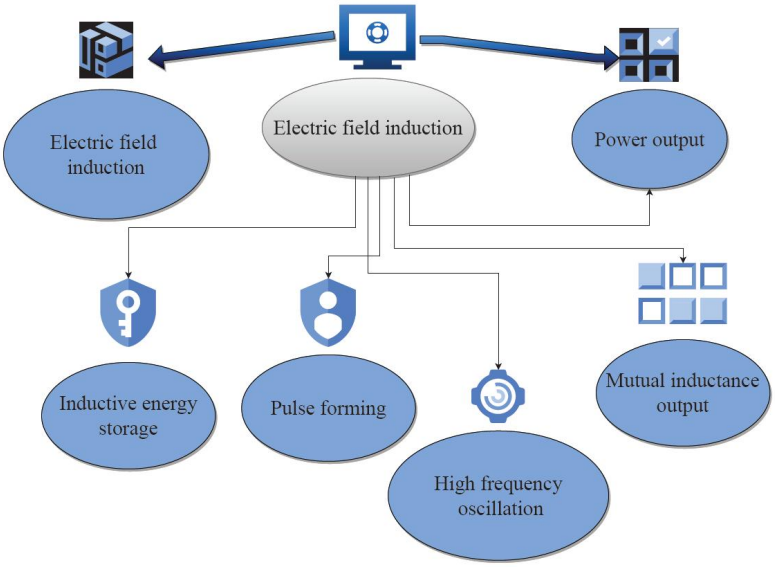

Figure 1. Working process of pulse power electric field induction energy extraction

Airborne conductor, as a suspended electrode, induces energy storage in the high-voltage electric field between the power line and the overhead ground wire, and maintains good insulation with them. At the same time, it is connected with a gas switch that remains disconnected and the high-voltage side of the pulse transformer, and forms an energy extraction circuit for suppressing discharge with the overhead ground wire. The mutual induction voltage is output from the low-voltage side of the pulse transformer after bridge rectification [8]. Realize the energy transfer of the first level, the lowest level is directly grounded, and no transformer is used for isolation, which is beneficial to improve the circuit efficiency. The other levels are the same. This design improves the total voltage of the energy level and improves the circuit power.

2.2 Suppression discharge principle

The air gap discharge forms a spark discharge plasma channel to connect the circuit, and the turn-on time is generally in the order of 10-8 s. During the discharge process, the air gap conductivity increases rapidly, and the discharge pulse current increases rapidly, and the rising speed is extremely fast. At present, the towers used in power system can be divided into five types according to their shapes: goblet type, upper type, dry type, barrel type and cat head type, among which the top part of the cat head type tower is convenient for fixing and installing metal plates, and the top of the tower has a closed electric field environment [9]. No matter what kind of induced electricity, the higher the voltage level, the greater the induced voltage and the greater the harm to the maintenance personnel. The simplest calculation model of lightning current waveform model at the bottom of lightning current channel is triangle model, which mainly includes three parameters, namely wavefront time, wave tail time and current amplitude [10]. Therefore, relevant equipment should be installed on the distribution line below the EHV line and corresponding measures should be taken to eliminate the induced voltage in the line to ensure the safety of maintenance personnel. Because of the special structure of this plate, adding a metal plate with such an area to the original transmission line electric field environment will inevitably have a certain impact on the original electric field. In order to verify its safety, the electric field near the transmission line before and after installing the plate is analyzed in this paper [11].

In the process of suppressing discharge, the gas switch plays the dual roles of pulse switch and oscillation at the same time, so the switch trigger and excitation control circuit are omitted. Because the pulse transformer is used to discharge, the main circuit bears a large impulse current, which will affect the service life of the equipment to some extent. At the same time, the electrical load is located at the low-voltage side of the pulse transformer and works in the flyback state, which has good electrical isolation between input and output and is suitable for discharging pulse power extraction [12]. In this paper, the way of electric field induction is used to obtain energy and supply power, and the design of the energy-obtaining polar plate is optimized. Through modular treatment, it is more conducive to wind protection and easier to install and maintain. At the same time, the charging circuit is developed based on inductance mode, which further improves the energy-obtaining power and overcomes the problem of impulse current.

2.3 Analysis of energy equivalent circuit

The reason for this change is that the electrostatic induction in the low-voltage line is generated by the capacitive coupling effect between the wires, and has no direct relationship with the transmission power in the high-voltage line. It is usually only used for qualitative analysis, and the results obtained by using the model in the extensive calculation often differ greatly from the actual situation. In the early calculation of lightning current waveform, the most widely used model is the double-exponential model.

The electromagnetic induction in the low-voltage line is caused by the alternating current in the high-voltage line, which produces the transformed magnetic field and thus the electromagnetic effect. The model is relatively simple in expression, easy to calculate and derive, and highly consistent with the measured natural lightning waveform, but its derivative at zero is not zero, which is not applicable to the field of simulation calculation [13]. It is quite difficult to directly solve the pulse rise time by using the non-linear resistance of spark gap changing with current and time proposed by Wezel, and the process of spark gap resistance changing from high resistance value to close to 0 can be characterized by the characteristic time θ with the increase of spark gap conductivity:

$$\theta = \frac{2pd}{aU} \tag{1}$$

Where p is the air gap pressure; d is the air gap distance, and a is the arc resistance coefficient; U is the breakdown voltage of the switch.

In general, the time for the spark gap resistance to drop far below the total impedance of the rest of the discharge circuit, and much shorter than the rising time of the discharge current. The details of the change of spark resistance are not very important. Considering that the energy recovery circuit has a large inductance element in series, the development time of the spark gap is ignored, and the gas switch is regarded as an ideal switch with no delay at the turn-on moment.

3. POWER APPLICATION TEST

3.1 Introduction to video device

When the distribution line is in a shutdown state, both ends of the line must be grounded immediately. Generally, the maintenance personnel of low-voltage distribution lines will ignore this operation, or in the grounding process, the operation is not scientific, which makes the grounding incomplete, causing serious safety hazards to the maintenance personnel and nearby residents. It is composed of USB camera, raspberry pie, 4G module and power module. The USB camera uses the common drive-free USB camera on the market. Raspberry pie is based on the Raspbian version of the operating system to drive the camera and 4G module. The USB camera captures video and pictures. Raspberry pie uses the 4G network to upload video and pictures to a specific server. When you need to view the device status, you can only download the corresponding information. The structure block diagram of the inductive energy source is shown in Figure 2. It includes the energy taking unit, the main control unit and the follow-up circuit. The energy taking unit includes two energy taking cores of different materials. The measuring coil measures the current on the line in real time as a control signal. The main control unit selects different magnetic cores by judging the current value.

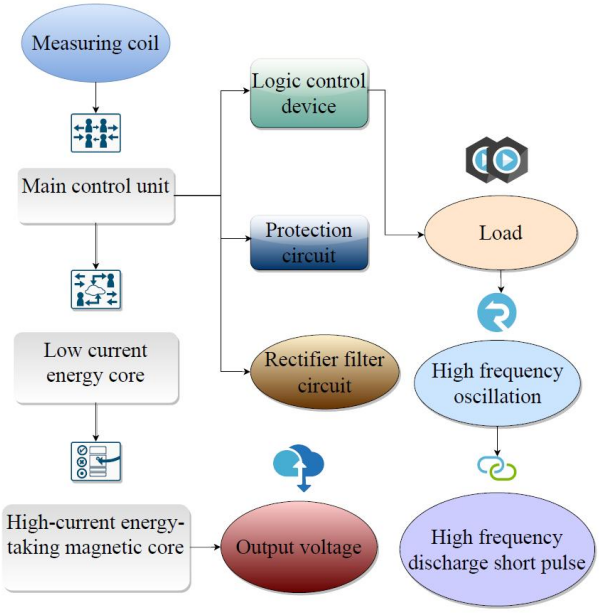

Figure 2. Structural block diagram of inductive energy harvesting power supply

According to the elimination method of temporary grounding of low-voltage distribution line, and then combined with relay and contactor control, the corresponding safety device can be designed. Its basic principle is that when the distribution line is in the state of power failure and maintenance, AC contactors and other devices will automatically ground both ends of the distribution line to eliminate the induced voltage in the line. After the distribution line is struck by lightning, the current will form a certain field line distribution excitation on the power transmission line, that is to say, the field line distribution excitation can establish a function in time and space, thus generating lightning-induced overvoltage. As shown in Table 1, the energy extraction power supply starts to work, and the dead zone is small. By

switching the tap or the magnetic core, the magnetic core is prevented from being over-saturated, and stable energy supply can be realized within the current variation range.

Table 1. Test data at 550 turns

Primary current	Effective value of load voltage	Remarks
100	7.45	Waveform recovery
500	30.14	Waveform start distortion
800	48.27	Deepening of distortion

The induced voltage elimination device is applied to the distribution line under 500kV. In the actual calculation process, the electric field perpendicular to the ground is less affected. In the design of energy extraction, more attention is paid to the suppression of energy extraction power in the process of discharge. In the process of suppressing discharge, the energy stored in the inductor is expressed as:

$$W_p = L_p i \frac{d_i}{dt} \tag{2}$$

Substitute t_s into the formula (2):

$$W_p = \frac{U_{ae} - U_{d0}}{2\omega L_p} \sin^2 \tag{3}$$

Then the average power of energy extraction is obtained:

$$P = W_p / t_s = U_{ac} \frac{-2\tan}{\pi\omega L_p} \tag{4}$$

It can be seen from formula (3) that the average power P will change with the change of power line voltage U_{ac}.

When the observation point is close to the lightning current, the horizontal electric field Ez is also less affected. This electric field can be calculated by the above formula. Through the analysis of simulation software, it can be concluded that due to the influence of inductance in the line, the voltage on the grounding resistance will rapidly drop to zero after a slight oscillation, thus effectively eliminating the induced voltage in the low-voltage line.

3.2 Comprehensive test

The distribution line is a high-voltage overhead line, and the occurrence of lightning induced overvoltage is a relatively complex natural phenomenon. In this paper, the simulation calculation model widely used by the current academic community can be more close to the calculation results under actual working conditions to a certain extent. Based on the power consumption of the video equipment and the time required to complete a video and image acquisition task, calculate the required energy and set the threshold voltage for the video equipment to start work. The measured value is 9.2V. Install automatic grounding device at both ends of low-voltage distribution line. Once the line is disconnected and needs maintenance, the grounding device can act quickly to ground both ends of the line, so as to eliminate the induced voltage and ensure the safety of line maintenance personnel.

When measuring the space electric field of a lightning stroke, the function waveform in the calculation results of the pilot stage is relatively slow, and the decline speed is closely related to the development speed of the pilot. When the waveform drops to the pole and rises upward, the speed is mainly related to the development speed of the lightning flow channel, and the waveform of the final stage is also dominated by the lightning flow. Carry out the experiment according to the size and installation position of the plate given in the paper, record the indication of the DC microammeter under different plate size and voltage, and simulate the parasitic capacitance under the corresponding plate size, calculate the corresponding induced current and record.

The plate size is 0.50m × The curves of experimental current and simulated current with voltage at 0.25m are shown in Figure 3. It can be seen that the simulation results are basically consistent with the experimental values, and the induced

current increases with the increase of voltage. When the line voltage is fixed at 50kV, the induced current generated under different plate sizes is measured and simulated. The change curve is shown in Figure 4. It can be seen that the simulation results are basically consistent with the experimental values, and the induced current increases with the increase of the plate, which is consistent with the theory that the capacitance value is proportional to the area of the plate in the principle of parallel plate capacitor.

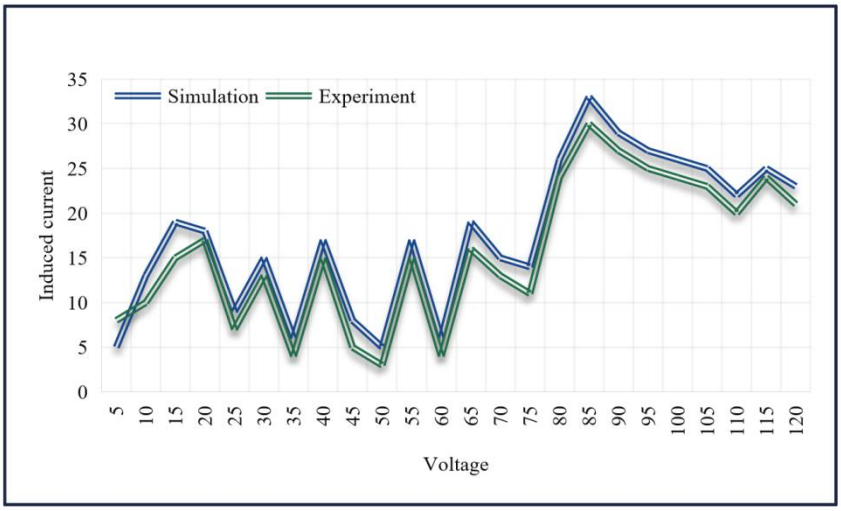

Figure 3. Induced currents corresponding to different voltages

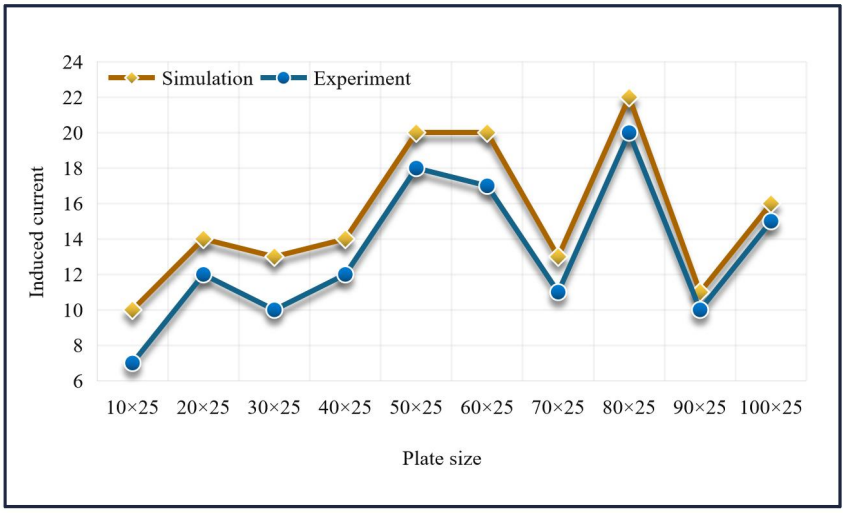

Figure 4. Induced currents corresponding to plates of different sizes.

The induced current distribution and the lightning withstand level of the line prove that the overhead ground wire can effectively improve the lightning withstand level of the line. No matter whether the plate size or voltage changes, the simulation results of finite element software are basically consistent with the experimental values, so we can know that the simulation results of the method proposed in this paper are desirable. However, the initial permeability is low, which is suitable for energy extraction at high current. Permalloy has a high initial permeability, but it is easy to saturate when the current is slightly larger. Microcrystalline alloy has high initial magnetic permeability, and it is easy to obtain large output at low current, which is suitable for energy extraction at low current and reduces the flashover probability of distribution lines during induction lightning.

4. CONCLUSIONS

A solution to the power supply problem of monitoring equipment placed on power towers is proposed. By using the principle of electric field induction, energy can be obtained from the electric field near high voltage transmission lines, which is stable and can be used for low power consumption and periodic operation equipment on the side of power towers. Due to the insulation characteristics of air, the space displacement current between the power line and the overhead ground wire is weak, and the direct electricity extraction energy and power are low, and the general electrical equipment can not directly withstand thousands of volts of high voltage. Therefore, even if the output energy and power of the electric field around the high-voltage transmission line meet the electricity demand, it can not be directly and effectively utilized, and it needs to be obtained by certain means. According to the elimination method of temporary grounding of low-voltage distribution line, and then combined with relay and contactor control, the corresponding safety device can be designed. Its basic principle is that when the distribution line is in the state of power failure and maintenance, AC contactors and other devices will automatically ground both ends of the distribution line to eliminate the induced voltage in the line. The simulation results show that the simulation results of finite element software are basically consistent with the experimental values, no matter the size or voltage of the electrode plate changes, so we can know that the simulation results of the method proposed in this paper are desirable. However, the initial permeability is low, which is suitable for energy extraction at high current. Permalloy has a high initial permeability, but it is easy to saturate when the current is slightly larger.

REFERENCES

[1] Bucci, G., Ciancetta, F., Fiorucci, E., et al., An internet-of-things system based on powerline technology for pulse oximetry measurements. ACTA IMEKO, vol. 9, no. 4, pp. 114-137 (2020).

[2] Samiyevich, Q. F., Using the Methods of Pulse Electric Field in the Technology of Extraction of Cotton Oilcake. Austrian Journal of technical and natural sciences, vol. 48, no. 56, pp. 61-74 (2019).

[3] Wang, B., Jianfei, S. I., Chunfeng, Y. U., A design of high voltage electric-field induction energy-acquisition based on pulsed power technology. Electric Power Engineering Technology, vol. 56, no. 24, pp. 36-57 (2022).

[4] Li, Z., Mei, H., Wang, L., A Power Supply Technology for a Low-Power Online Monitoring Sensor Based on Electric Field Induction. Sensors, vol. 19, no. 9, pp. 2169-2178 (2019).

[5] Han, S. F., Jin, W., Yang, Q., et al., Application of pulse electric field pretreatment for enhancing lipid extraction from Chlorella pyrenoidosa grown in wastewater. Renewable Energy, vol. 133, no. 55, pp. 233-239 (2022).

[6] Meng, M., Zhang, Y. J., Yang, N., et al., Efficient Extraction of Tricholoma matsutake Polysaccharide by Magneto-Induced Electric Field and Its Process Optimization. Science and Technology of Food Industry, vol. 15, no. 2, pp. 11-19 (2019).

[7] Yan, X. F., Zhu, C. Q., Shi, K. R., et al., Laser Power Supply Technology in Pulse Electric Field Test. Chinese Journal of Luminescence, vol. 40, no. 2, pp. 264-271 (2019).

[8] Peng, W., A Study on the Application of the High-Voltage Pulse Power Source Technology in Electrostatic Precipitation. Journal of Chongqing Electric Power College, vol. 22, no. 14, pp. 35-58 (2021).

[9] Meng, L. V., Niu, C. X., Research on High Power Electrochemical Pulse Power Technology. Science & Technology Vision, vol. 63, no. 20, pp. 31-45 (2022).

[10] Zheng, L. I., Gao, S., Zhang, Y., et al., Underwater radio power transmission based on electric field induction. Journal of Hebei University of Science and Technology, vol. 25, no. 20, pp. 21-42 (2021).

[11] Li, Z., Liu, L., Fan, Y., et al., Title: Kinetic modeling for high voltage electrical discharge extraction based on discharge energy input. Food Chemistry, vol. 314, no. 4, pp. 126168-126177 (2020).

[12] Chen, Y., Kozlovskiy, V., Du, X., et al., Increase of the particle hit rate in a laser single-particle mass spectrometer by pulse delayed extraction technology. Atmospheric Measurement Techniques, vol. 13, no. 2, pp. 941-949 (2020).

[13] Kayimov, F., Extraction of the cotton cake by the influence of pulse electric field. Chemistry and Chemical Engineering, vol. 20, no. 3, pp. 12-52 (2019).