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Research on Ferromagnetic Resonance of Electromagnetic Voltage Transformers in Shale Gas Field Distribution Network

Zhixuan He

Shanghai University of Technology, School of Mechanical Engineering Shanghai, China

Abstract

The shale gas field has vigorously implemented the "electricity replacing oil" extraction method. Promoting the wide application of distribution network automation technology in shale gas distribution networks. Regarding the frequent occurrence of ferromagnetic resonance faults caused by the saturation of electromagnetic voltage transformers. The current research fails to take into account the load characteristics and actual working conditions. This paper, based on the electromagnetic transient simulation software PSCAD, establishes a PT ferromagnetic resonance model for the 10kV non-grounded system of the Changning Shale Gas Field. The simulation analyzed the effects of line length, conductor cross-section and excitation conditions on ferromagnetic resonance, and proposed suppression measures for the PT high-voltage side through a linear resistor connection. The simulation results show that when the length of the line meets the resonance condition, an increase in length will lead to an increase in the amplitude and frequency of the resonant overvoltage. When considering the cross-sectional area of the electrical conductor, the overcurrent on the PT high-voltage side of the fracturing-specific line is greater than that of the conventional line, which is prone to causing the fuse to blow. The influence of excitation conditions on resonant overvoltage varies greatly. The resonant amplitude triggered by arc grounding faults is the highest. Finally, a protective measure is proposed where the neutral point of the primary winding of the PT is connected to a non-linear resistor, in order to prevent the frequent occurrence of resonance accidents.

Keywords

Shale Gas Field; Distribution Network; Ferromagnetic Resonance; Electromagnetic Voltage Transformer; In recent years; a series of policies have been introduced.

1. INTRODUCTION

Under the background of the "dual carbon" goals, shale gas, as a clean and high-efficiency energy source, has been identified as a key priority for development and utilization in China. In recent years, a series of supportive policies have been issued, such as the *Measures for the Administration of Special Funds for the Development of Clean Energy*, which provides an incremental reward and subsidy policy of "more increases, more subsidies" for shale gas exploitation, with additional incentives for the incremental output during the heating season [1]. These policies have effectively boosted the reserve enhancement and production growth of shale gas. With the continuous advancement of integrated shale gas development, traditional diesel generators can no longer meet the power supply demands of high-power equipment such as electric drilling rigs and electric-driven fracturing pumps. The "oil-to-electricity" fracturing mode has been extensively implemented in the shale gas fields of Sichuan and Chongqing, and regional distribution networks have been gradually constructed [2].

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With the increasing digitalization and transparency of distribution networks, automation devices in shale gas field distribution networks are equipped with a large number of measurement and control components, which generally adopt PTs for signal measurement and operating power supply. The operational status of PTs is directly related to the safe and reliable operation of distribution networks. The 10 kV distribution networks in shale gas fields usually operate in a neutral ungrounded or arc suppression coil grounded mode. When a single-phase grounding fault occurs or external disturbances arise in the system, the iron core of PTs is prone to saturation, which makes the self-inductive reactance of PTs match the system's capacitive reactance to ground in terms of parameters, thus triggering ferromagnetic resonance. This phenomenon may lead to overvoltage, overcurrent and even PT burnout [3].

Scholars at home and abroad have conducted extensive research on ferromagnetic resonance caused by PT saturation. Reference [4] investigated the conditions for the occurrence of various oscillations, pointing out that the system will experience ferromagnetic resonance of varying degrees with changes in system parameters. Reference [5] analyzed the total harmonic distortion rate of the primary side current of PTs under different saturation characteristics in a cable hybrid line system. Reference [6] explored the effects of ground capacitance and PT excitation characteristics on ferromagnetic resonance during the live-line operation of PTs in distribution networks under non-power-off conditions, and proposed a method for PT resonance identification. Reference [7] combined the ferromagnetic resonance phenomenon occurring in a certain converter station, clarified the causes of ferromagnetic resonance in the high-voltage direct current (HVDC) and series-compensated alternating current (AC) system through theoretical analysis and simulation verification, and put forward a corresponding suppression measure. In addition, many scholars have carried out in-depth research on PT ferromagnetic resonance through various technical approaches including theoretical derivation [8-9], experimental research [10] and computer simulation [11-12], and proposed a series of suppression measures. However, some of these measures have limited effectiveness in practical engineering applications.

In summary, existing research on ferromagnetic resonance mainly focuses on the distribution networks of power plants and substations themselves, while there are few studies on distribution networks considering load characteristics and different operating conditions in practical engineering. Based on the PSCAD software, this paper establishes a simulation model of the distribution network in shale gas fields, simulates electromagnetic PTs with the TYPE98 model, and studies the impacts of line length, economic line cross-section and different excitation conditions on PT ferromagnetic resonance under specific operating conditions. A suppression measure of grounding the high-voltage side of PTs through linear resistors is proposed to improve the reliability and safety of power grid operation in shale gas fields.

2. RELATED WORK

2.1. System Topology and Operation Mode

Taking the Changning shale gas field, which has relatively advanced production equipment, as the research object. The 110 kV bus of the system adopts a single-bus sectional connection mode, with two 110 kV overhead dedicated lines drawn from the local substation as power supply incoming lines, which operate simultaneously and serve as mutual backups.

Shale gas fields are usually located in mountainous areas or fault-developed zones, and the development areas are fragmented due to the need to bypass fault zones, resulting in a large total area but a small effective development area. A 110 kV substation with a voltage grade of 110/10 kV is constructed at the center of each well area in the gas field. Conventional substations are not suitable for mountainous areas due to their large floor area and long

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construction period, therefore, a 110 kV skid-mounted integrated mobile substation is adopted in the design.

The 110 kV system is stepped down to 10 kV through the transformer SSZ11-50000/110, and the 10 kV bus also adopts a single-bus sectional connection mode, equipped with PTs and reactive power compensation equipment [13]. The 10 kV overhead outgoing lines of the substation supply power to both conventional gas production loads and phased loads such as fracturing pumps simultaneously.

2.2. Analysis of Main Loads of Gas Wells

The main electrical equipment in the shale gas exploitation process includes grid-powered drilling rigs, fracturing units, electric-driven compressors and other gas production equipment. Compared with the large-scale shale gas exploitation in the United States, shale gas in China is buried at a great depth of more than 3500 meters. To meet the drilling depth requirements of drilling rigs in the exploitation process [14], a set of 70-type grid-powered drilling rigs including two 1200 kW motors is selected for drilling construction in this block.

The load is relatively large in the drilling and fracturing stage of the early production period, with the drilling power ranging from 2000 kW to 2400 kW. The fracturing unit has a displacement of 20 m^3/min and a maximum pressure of 60 MPa, with a main fracturing power of 33723 kW and an auxiliary power of 2000 kW. The power of the pumping plunger is 2761 kW, and the power of CO_2 injection is 4141 kW, with the maximum simultaneous load of the unit reaching 42.6 MW. The drilling cycle of a single well is about 60 days, while the fracturing cycle is only about 10 days, which is characterized by large load, significant fluctuation and strong impact on the power grid.

The load is relatively small in the gas production stage of the later production period, mainly including a 300×10^4 m^3/d dehydration device and two 800 kW high-voltage electric-driven compressors in the dehydration station; 2~3 800 kW high-voltage electric-driven compressors in 8 gas gathering stations; and one 315 kW high-voltage electric-driven compressor in 15 platform well stations, with a total load of about 22000 kW. The gas production cycle lasts for decades, which is characterized by small load fluctuation compared with the early production period.

Shale gas in China is buried at an ultra-deep depth, resulting in a huge power supply load for shale gas exploitation and production. Line loss increases with the extension of line length. To effectively reduce line loss, 110 kV substations are built at the load centers of each well area, leading to long 110 kV lines and short 10 kV lines. The PTs connected to the 10 kV bus are prone to parameter matching with the 10 kV line parameters, which may trigger severe ferromagnetic resonance.

2.3. Line Performance and Economy

Overhead lines account for a high proportion of investment in the entire line project. A small conductor cross-section can save investment costs, while a large cross-section can reduce power loss. The process of determining a relatively reasonable conductor cross-section through comprehensive consideration of investment and power loss is referred to as the economic conductor cross-section.

In this paper, the economic analysis of conductors is carried out based on the minimum annual cost model to determine the optimal conductor cross-section [15]. The total annual cost is the sum of the annual investment cost and the annual power loss cost, where the annual investment cost is expressed as:

$$C_b = (C_1 + C_2)(a + bS)$$

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The investment recovery factor C_1 is calculated as:

$$C_1 = \frac{r_0(1+r_0)^n}{(1+r_0)^n - 1}$$

In the formula: n is the loan term, taking 20 years; r_0 is the annual interest rate, taking 5% according to the national loan interest rate in recent years, with the calculated value of C_1 being 0.08. C_2 is the line depreciation and maintenance rate, taking 0.1013 for medium and low-voltage lines in general; a is the fixed cost base of the line per unit length (yuan/km); b is the material cost of the line per unit length which is linearly related to the conductor cross-section (yuan/(mm^2·km)). Reference [16] fitted the investment cost of low-voltage overhead lines with different cross-sections, and the fitting curve is highly correlated with the cross-section S, with the value of b determined as 684.21 yuan/km.

The annual power loss cost is obtained by multiplying the theoretical line loss electric quantity by the corresponding electricity price, expressed as:

$$C_w = \Delta A \beta G_P \times 10^3$$

The line loss W_{loss} can be expressed as:

$$\Delta A = K I_M^2 \rho \tau / S$$

In the formula: K is related to the power supply mode of the line; in low-voltage distribution networks, the three-phase four-wire system is generally adopted to adapt to three-phase unbalanced loads, with K taking 3.5. I_{M} is the maximum load current of the line (A); ρ is the conductor resistivity (Ω·mm^2/km); τ is the number of hours of maximum load loss (h); S is the conductor cross-section (mm^2). ρe is the electricity price (yuan/(kW·h)); G_{P} is the power loss coefficient considering different load distributions of the line. Reference [17] gives the value of G_{P} as 1 for medium and low-voltage lines under the end concentrated load distribution mode.

The total annual cost is expressed as:

$$Z = C_b + C_w = (C_1 + C_2)(a + bS) + K I_M^2 \rho \tau \beta G_P / (S \times 10^{-3})$$

Therefore, there exists an economic conductor cross-section $S*$ that minimizes the total annual cost. By taking the derivative of Z with respect to S, the economic current density J is derived as:

$$J = \frac{I_M}{S} = \sqrt{\frac{(C_1 + C_2)b}{K \rho \tau \beta G_P \times 10^{-3}}}$$

Electric-driven fracturing is a typical phased load in shale gas exploitation. In recent years, the "well factory" mode has become the core of shale gas development, that is, multiple horizontal wells are drilled on the same platform, and fracturing operations are carried out centrally after the completion of drilling to achieve efficient development. Conventional gas production loads operate all year round, with the number of hours of maximum load loss τ much larger than that of fracturing loads. In this paper, τ for fracturing loads and conventional loads is set to 1200 h and 4600 h, respectively.

For the same voltage grade, electricity price and other parameters, the economic conductor cross-sections of fracturing lines and conventional gas production lines are calculated as 62.8 mm^2 and 183.7 mm^2 based on Formula (6), respectively. Combined with the specifications of

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LGJ-type conductors, LGJ-70 and LGJ-185 conductors are selected for fracturing lines and conventional gas production lines, respectively.

The conductor cross-section is not only related to economic benefits but also affects system parameters. Therefore, in shale gas field distribution systems, different loads may lead to different resonance frequencies and severity levels of ferromagnetic resonance. In the distribution network planning stage, it is necessary to balance economy and reliability through simulation calculation.

3. METHOD

3.1. Mechanism Analysis of PT Ferromagnetic Resonance Faults

In a neutral ungrounded system, under normal operating conditions, the inductive reactance of PTs is greater than the capacitive reactance of lines, and the resonance condition is not met at this time. When the system is disturbed (e.g., a single-phase grounding fault), the neutral point shifts and a zero-sequence voltage is generated. The transient energy accumulated in the non-fault phases can only be released through the grounding point of the primary side neutral point of PTs after the fault is eliminated. Due to the excitation characteristics of PTs, the inrush current causes magnetic saturation of the PT iron core, and its inductive reactance decreases accordingly. When the inductive reactance of PTs is equal to the capacitive reactance of lines, resonant overvoltage will be induced, and the circuit for triggering the ferromagnetic resonance process is shown in Fig. 1 [4].

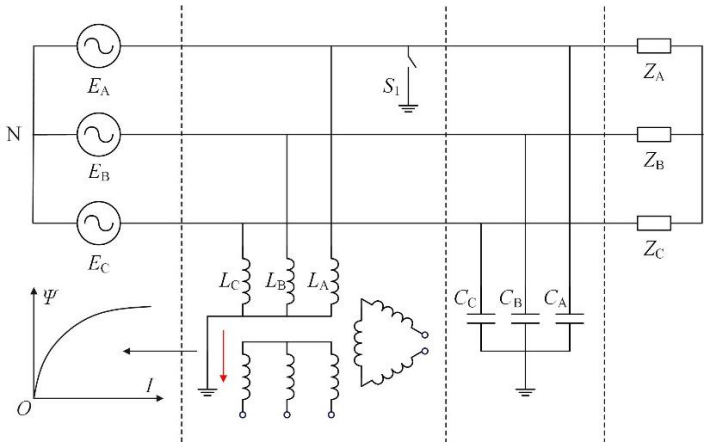


Figure 1. Circuit for stimulating ferromagnetic resonance

In Fig. 1, the primary winding of the electromagnetic PT is connected in Y_0 mode, E_A, E_B and E_C are the three-phase voltages on the power supply side, L_A, L_B and L_C are the excitation inductances of the PT to ground for each phase, and C_A, C_B and C_C are the equivalent capacitances of the system to ground for each phase. Let the equivalent admittances of the parallel connection between the excitation inductance and the equivalent capacitance to ground for each phase be Y_A, Y_B and Y_C, respectively. Assuming the neutral point displacement voltage of the system is E_0, the following equation can be obtained:

$$E_0 = -\frac{E_A Y_A + E_B Y_B + E_C Y_C}{Y_A + Y_B + Y_C}$$

Under normal system operation, the PT iron core is in an unsaturated state with a high excitation inductance, and $Y_A=Y_B=Y_C$, resulting in the system neutral point voltage $E_0=0$. If the system is subjected to external disturbances, taking phase A as the grounding fault phase for example, when the fault is eliminated and the switch S_1 is switched from closed to open, the PT iron core becomes saturated, and the inductive current of the non-fault phases will exceed the

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capacitive current, that is, a phase inversion phenomenon occurs, and the equivalent admittance changes from capacitive to inductive [11]. At this time, a potential difference is generated between the capacitive voltage of the non-fault phases and the system power supply, and a series resonance loop is formed with the capacitance and inductance of the fault phase, as shown in Fig. 2.

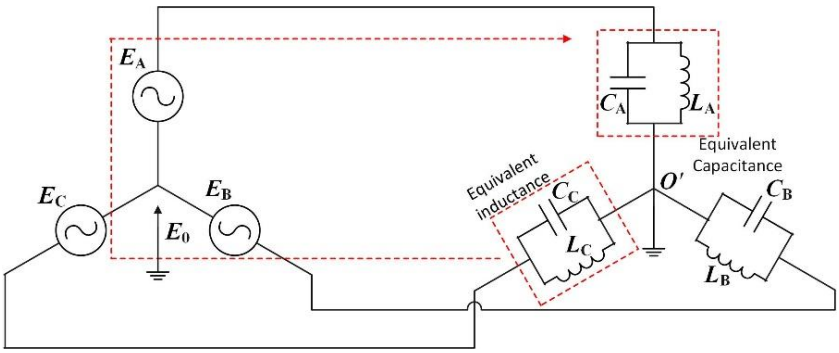


Figure 2. Equivalent circuit after system fault elimination

At this time, the fault phase A is capacitive, and phases B and C are inductive. The equivalent capacitance of phase A is C, and the equivalent inductances of the two saturated phases B and C are L_B=L_C=L. Substituting into Formula, the following equation is obtained:

$$\dot{E}_0 = -\dot{E}_A \frac{\omega C + 1/(\omega L)}{\omega C - 2/(\omega L)}$$

It can be deduced from ωC+1/(ωL)>ωC−2/(ωL) that the neutral point displacement voltage E_0 is in anti-phase with E_A, and E_0>E_A, indicating the occurrence of neutral point voltage shift, whose vector relationship is shown in Fig. 3.

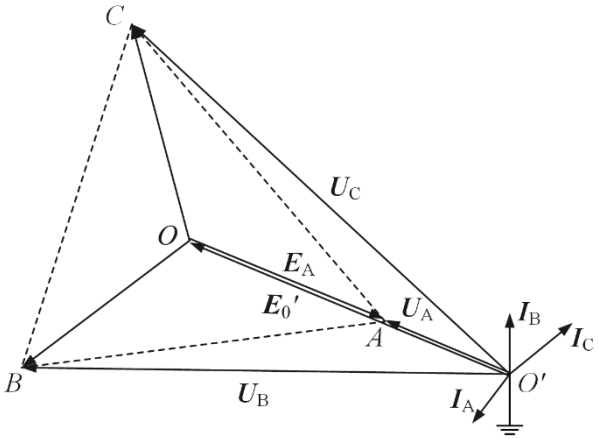


Figure 3. Vector relationship diagram of unsaturated phase A on the primary side of the PT

The ground voltage of the two saturated phases B and C rises and exceeds the line voltage, while the ground voltage of the unsaturated phase A decreases but is not zero. This phenomenon is similar to the situation where a single-phase short-circuit grounding fault occurs in the system, which is referred to as "illusory grounding". This phenomenon will cause the grounding indicating device to malfunction and send out a grounding signal, leading to misjudgment by the operating staff.

In the actual operation of shale gas field power grids, the excitation saturation state of PTs is complex and changeable. The amplitude of three-phase voltage and resonance frequency are affected by the system inductance and capacitance parameters, and the variation of three-phase ground voltage is also complex, which in turn will induce PT ferromagnetic resonance

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overvoltage of different types and degrees. When analyzing the ferromagnetic resonance faults caused by PT saturation, it is necessary to focus on the impacts of PT inductive and capacitive parameters on the resonance process.

3.2. Establishment of Simulation Model for Shale Gas Field Distribution Network

Referring to the actual operation diagram of the Changning Shale Gas Field Substation, a simulation model is built by using the PSCAD software [1]. The simulation model consists of a 110 kV line area with single-bus operation and a 10 kV line area with single-bus sectional operation. The parameters of the load module are shown in Table 1, where L1-L3 are conventional gas production lines, L4 is an electric drilling rig line, and L5-L6 are fracturing-dedicated lines. The components of the simulation model include an electromagnetic PT module, a power supply module, a line module, a fault module, a switch module and a distribution transformer module. The overall topology is shown in Figure 4.

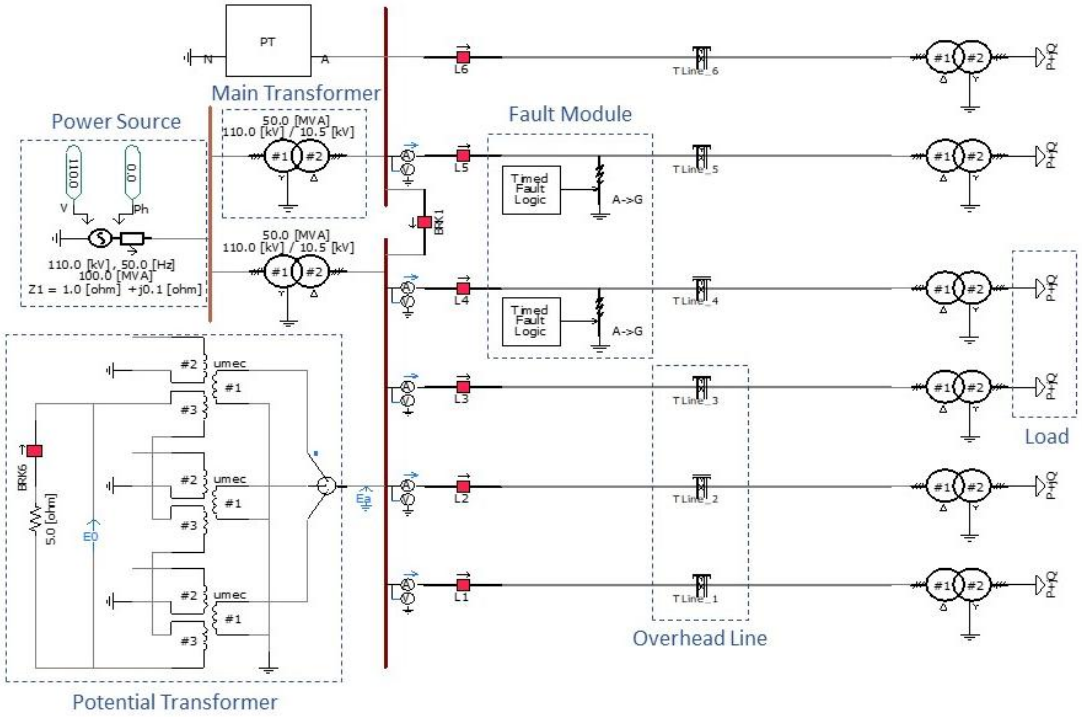


Figure 4. Vector relationship diagram of unsaturated phase A on the primary side of the PT

Since there is no ready-made PT module in the component library of the PSCAD electromagnetic transient analysis software, the PT in the simulation is equivalent to a single-phase two-winding transformer based on the unified magnetic equivalent circuit [18]. The nonlinear excitation characteristic is the fundamental cause of ferromagnetic resonance, so the full consideration of nonlinearity is the key to building an accurate PT model.

For the three-phase electromagnetic PT model, the PT capacity is set to 300 VA, the rated voltage is 10 kV, and the connection group is Y0/Y0/D. The specific parameters of the PT are shown in Table 1.

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Table 1. PT setting parameters

Parameter	Value
Capacity/MVA	300×10^{-6}
Winding 1 phase voltage/kV	5.77
Winding 2 phase voltage/kV	0.0577
Winding 3 phase voltage/kV	0.1
Rated operating frequency/Hz	50
Leakage reactance per unit value	0.1
No-load loss per unit value	0.001
Copper loss per unit value	0.0026

Power supply module: The power supply capacity is set to 100 MVA, the high-voltage side voltage is 110 kV, the phase angle of phase A is set to 0°, the operating frequency is 50 Hz, the internal impedance is 20.35 Ω, and the impedance angle is 80.05°.

Distribution transformer module: Two identical 63 MVA transformers are adopted, with the connection group set to Y0/Y/D.

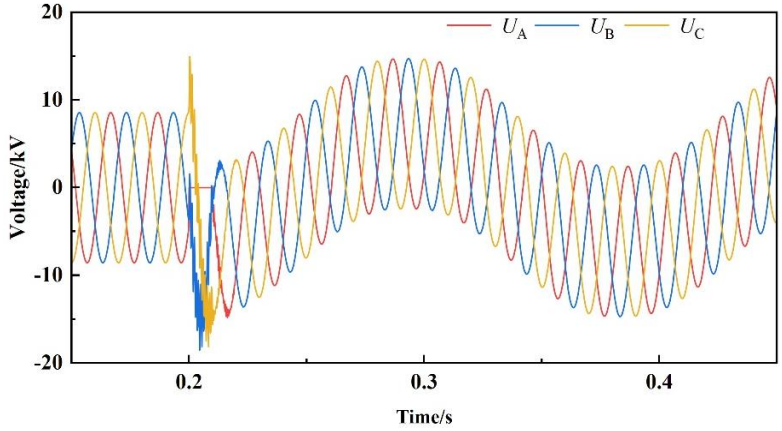
4. EXPERIMENT

4.1. Influence of Line Length on Ferromagnetic Resonance

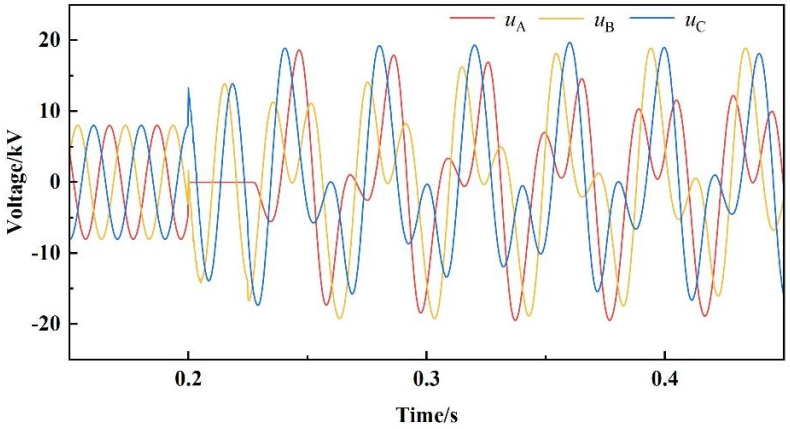
Based on the built shale gas field distribution network circuit model, a simulation is carried out to analyze the influence of line parameters (described in Section 1.2) on ferromagnetic resonance. A single-phase grounding fault is set to occur on the line at 0.2 s, the fault duration is 0.01 s, and the fault phase is phase A.

The system's capacitance to ground is adjusted by changing the length of the branch line, and the ferromagnetic resonance fault simulation is carried out with the system's capacitance to ground as the variable and other condition’[s unchanged. The ferromagnetic resonance simulation waveforms when the system's capacitance to ground is 100 nF and 1000 nF are shown in Fig. 5, and the three-phase voltage waveforms during 0.1~0.8 s are selected for amplified analysis. The relationship between the system's capacitance to ground, resonance frequency and overvoltage amplitude is shown in Fig. 6.

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(a) PT high-voltage side voltage at C=1000 nF



(b) PT high-voltage side voltage at C=15 nF

Figure 5. Ferromagnetic resonance simulation waveforms of PT under different system capacitances to ground

As shown in Fig. 5(a), after the elimination of the single-phase grounding fault, the three-phase voltage increases instantaneously with an amplitude of 14.4 kV, indicating a violent fluctuation of the bus voltage with an overvoltage amplitude of 1.4~1.5 pu, which means the system generates subharmonic resonant overvoltage. It can be seen from the PT voltage waveform in Fig. 5(b) that the three-phase voltage waveform presents a sharp peak, and the overvoltage amplitude reaches 19.3 kV, which is about 2.4~2.5 times the rated operating voltage of PTs. At this time, the system generates fundamental frequency resonant overvoltage, which will cause insulation breakdown and further lead to serious overcurrent phenomena.

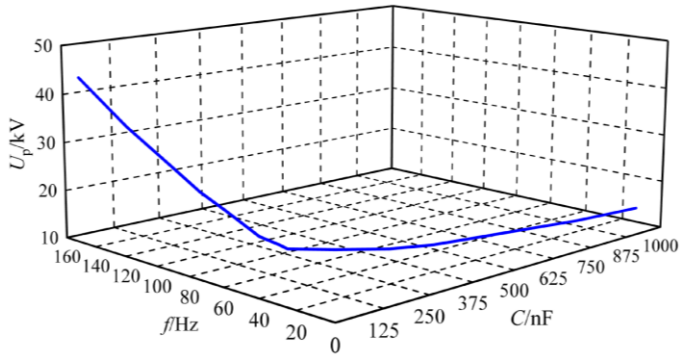


Figure 6. Three-dimensional map of the relationship between capacitance to ground, resonance frequency and overvoltage amplitude

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As shown in Fig. 6, when the system's capacitance to ground increases from low to high, the maximum amplitude of resonant overvoltage presents a nonlinear attenuation characteristic, with its inflection point appearing near 200 nF. When the capacitance to ground exceeds 200 nF, the overvoltage amplitude tends to be stable. The system is prone to high-frequency resonance under low capacitance conditions, with the resonance frequency being 2~3 times the power frequency. With the increase of the system's capacitance to ground, the frequency of ferromagnetic resonance gradually decreases; after the frequency decreases to the power frequency, the attenuation rate slows down, and subharmonic resonance with a frequency of 20~30 Hz is generated.

In the engineering practice of shale gas exploitation, controlling the line length can effectively reduce line loss and investment costs. However, the reduction of line length will lead to the decrease of capacitance to ground, which makes the system more likely to generate severe resonant overvoltage. Therefore, in shale gas field distribution systems, it is necessary to attach great importance to the measures for suppressing resonant overvoltage. In the distribution network planning stage, the influence of line parameters on resonance should be fully considered while taking line loss and investment into account.

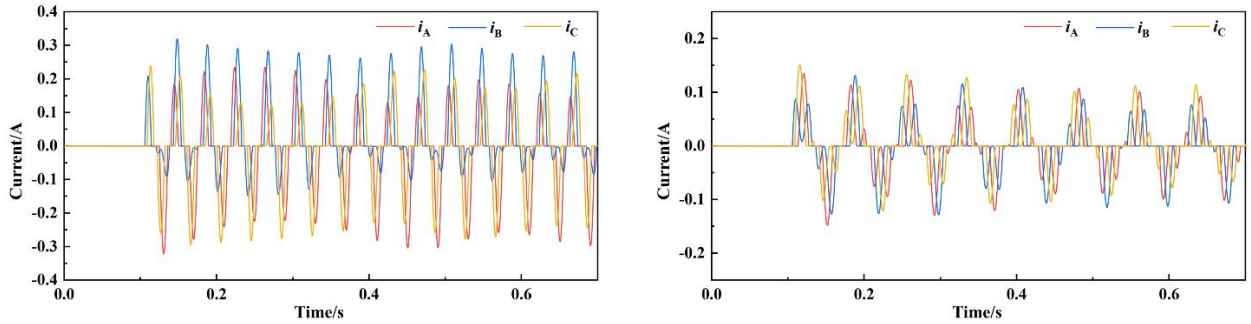
4.2. Influence of Line Cross-Section on Ferromagnetic Resonance

Through the line economic analysis in Chapter 2, the cross-section of fracturing-dedicated lines is smaller than that of conventional outgoing lines in line planning. Referring to the relevant technical manual, the fracturing-dedicated lines L6-L7 adopt LGJ-70/10 steel-cored aluminum stranded wires with an outer diameter of 11.40 mm, an aluminum stranded wire cross-section of 70 mm^2 and a steel stranded wire cross-section of 10 mm^2. The remaining lines adopt LGJ-185/25 conductors with an outer diameter of 18.9 mm, an aluminum stranded wire cross-section of 185 mm^2 and a steel stranded wire cross-section of 25 mm^2.

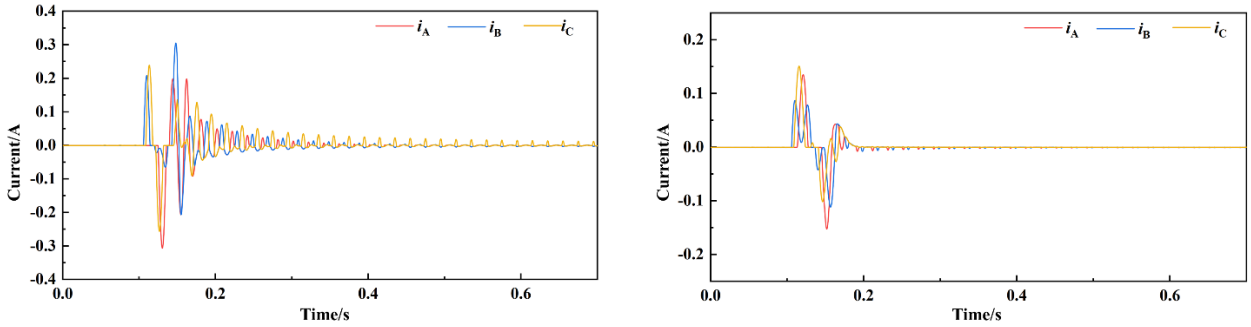
To verify the influence of line cross-section on PT ferromagnetic resonance in distribution networks, the PTs on fracturing-dedicated lines and conventional feeders are compared, and their primary side current waveforms are analyzed. The simulation results are shown in Fig. 8. As shown in Fig. 7(a), severe ferromagnetic resonance occurs in the PT on fracturing-dedicated lines, and the overcurrent on the high-voltage side of the PT exceeds 0.3 A, which exceeds the thermal stability level of PT equipment and will cause fuse blowing during long-term operation. Ferromagnetic resonance also occurs in the PT on conventional feeders, but the resonance current is significantly less than 0.2 A.

Connecting a damping resistor in parallel at the open delta of PTs can consume the excess charge generated by resonance. The simulation results are analyzed to explore its suppression effect on PT ferromagnetic resonance, and the waveform after suppression is shown in Fig. 7(b). The suppression effect of connecting a resistor in parallel at the open delta is excellent. By comparison, there is still a large overcurrent at the initial stage of resonance in the PT on fracturing-dedicated lines, while the resonance on conventional lines is quickly eliminated after generation. The simulation results show that the smaller the line cross-section, the more serious the ferromagnetic resonance generated and the more difficult it is to suppress.

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(a) PT high-voltage side current waveforms of fracturing lines and conventional lines



(b) PT high-voltage side current waveforms after connecting damping resistor in parallel at PT open delta

Figure 7. PT high-voltage side current waveforms of different lines

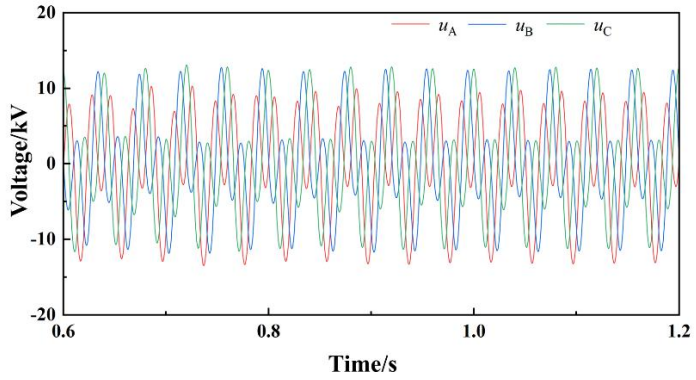
4.3. Influence of Excitation Conditions on Ferromagnetic Resonance

A model of bus section II with partial feeders is adopted, with the same line length and fault time set, to carry out a simulation study on different excitation conditions of ferromagnetic resonance overvoltage, including metallic grounding fault, grounding fault through resistors of different resistance values and arc grounding fault [19].

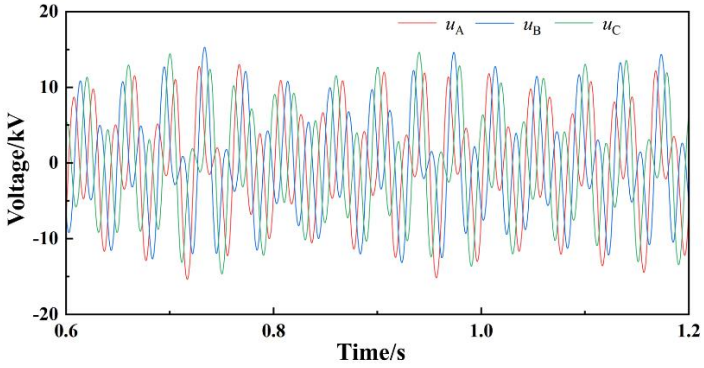
It can be seen from the simulation waveforms of PT ferromagnetic resonance overvoltage caused by different fault types (shown in Fig. 8) that the fault excitation type exerts a significant impact on ferromagnetic resonance. Compared with metallic grounding fault and grounding fault through resistors, the ferromagnetic resonance overvoltage waveform induced by arc grounding fault has a higher amplitude close to 20 kV, while the resonance amplitude induced by metallic grounding fault and grounding fault through resistors is below 15 kV. At the same time, arc grounding fault induces the highest resonance frequency, and the three-phase voltage symmetry is poor after the elimination of arc grounding.

The resonance energy induced by the elimination of arc grounding is large, leading to a high degree of PT saturation and thus more serious resonant overvoltage. In shale gas field distribution networks, the larger the capacitance to ground, the more likely the arc grounding fault is to occur. The previous simulation results show that the severity of ferromagnetic resonance increases with the increase of capacitance to ground. It is obviously not feasible to avoid more serious ferromagnetic resonance by increasing the line length and cross-section, so a more effective suppression measure needs to be proposed.

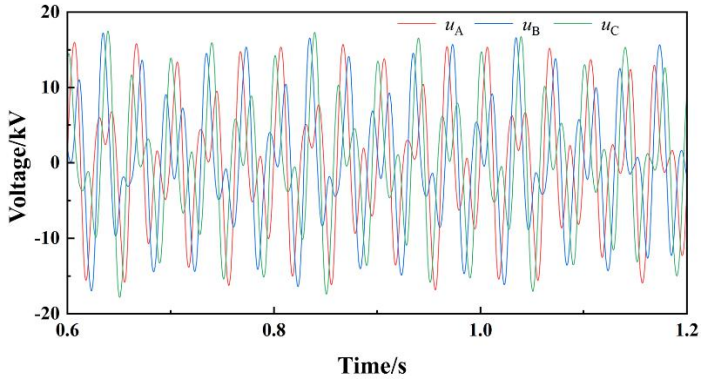
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(a) Excited by metallic grounding fault



(b) Excited by impact load fluctuation



(c) Excited by arc grounding fault

Figure 8. Resonant overvoltage waveforms excited by different fault types

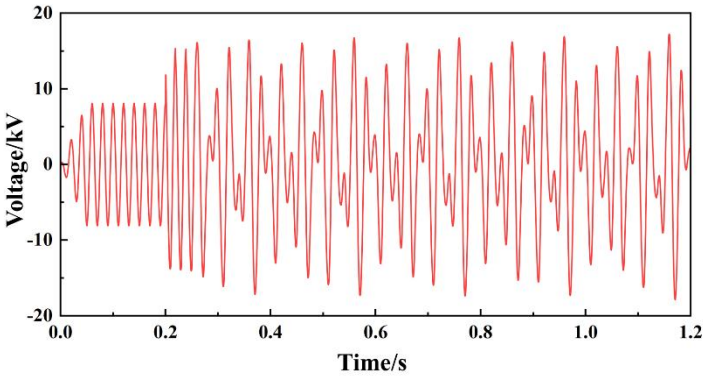
4.4. Suppression Measure of Grounding PT High-Voltage Side Through Resistors

Changing the grounding mode of the neutral point on the PT high-voltage side to grounding through resistors can restrict the transient amplitude of the PT winding current and effectively alleviate the magnetic saturation effect of the PT iron core. In addition, when the shale gas field distribution network operates at a high load or is subjected to external disturbances, the line voltage rises, the current flowing through the grounding resistor increases, the voltage at its two ends and the voltage division ratio increase, and the voltage division ratio of the PT excitation inductance decreases, thus reducing the saturation degree of PTs [20].

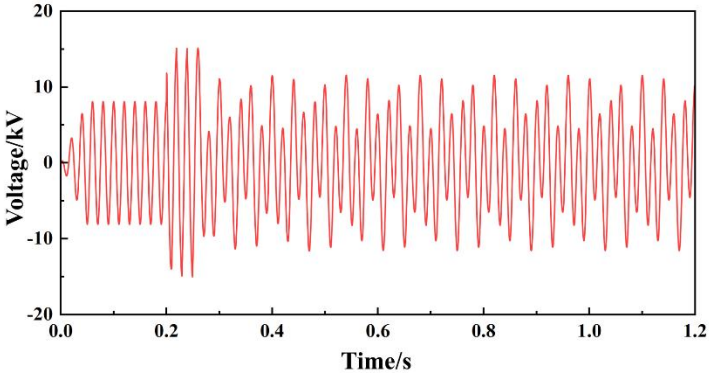
The neutral point on the high-voltage side of each phase of PT is directly grounded or grounded through linear resistors with resistance values of 12 kΩ and 20 kΩ, respectively. A fault is set to occur at 0.2 s with a duration of 0.05 s, and the simulation results are shown in Fig. 9. When the neutral point is directly grounded, the system generates severe ferromagnetic

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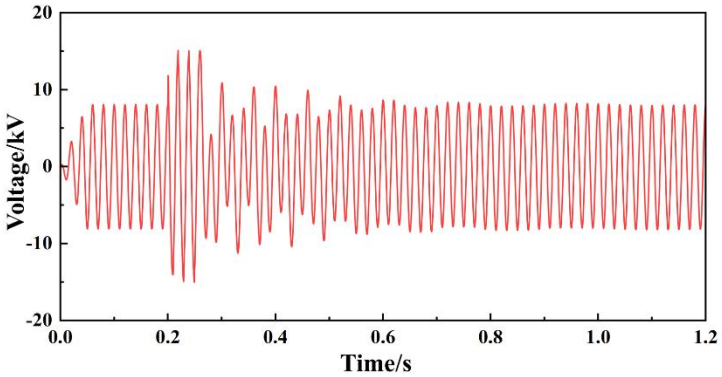
resonance with an overvoltage close to 20 kV. When the neutral point is grounded through a 12 kΩ linear resistor, the maximum overvoltage of phase A does not exceed 15 kV, and the resonant overvoltage is not completely eliminated. When the resistance value is increased to 20 kΩ, the overvoltage caused by resonance is suppressed below 10 kV, and the voltage returns to the rated value at 0.6 s, achieving an effective suppression of ferromagnetic resonance. Through multiple rounds of simulation calculations with different resistance values, it is verified that the suppression effect of this measure is not linearly related to the resistance value, and a reasonable selection of the resistance value can effectively coordinate the cost input and service efficiency.



(a) Neutral point directly grounded



(b) Neutral point grounded through 12 kΩ resistor



(c) Neutral point grounded through 20 kΩ resistor

Figure 9. A-phase voltage waveform on PT high-voltage side

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5. CONCLUSION

Starting from the actual engineering needs of shale gas field distribution networks, and based on the characteristics of the actual load and distribution network topology of shale gas fields, this paper establishes a PT ferromagnetic resonance fault simulation model that is basically consistent with the operating conditions of shale gas field distribution networks by using the PSCAD software. Through the in-depth analysis of the influencing factors of resonant overvoltage and the corresponding suppression measures, the following conclusions are drawn:

(1) The system's capacitance to ground is a key factor affecting the amplitude and frequency of resonant overvoltage. When the capacitance to ground is small, the system is prone to high-frequency resonance, which leads to severe overvoltage and endangers the safe operation of the distribution network. In actual production activities, the line length of shale gas field distribution networks may be fixed and short due to the geographical location of the main substation and the need to reduce line loss and investment costs. Therefore, effective suppression measures are urgently needed to avoid equipment damage and ensure the personal safety of operating personnel.

(2) The annual maximum utilization hours of fracturing loads are much shorter than those of conventional loads, and the economic cross-section of fracturing lines calculated by the minimum annual cost model is smaller than that of conventional lines. The smaller the line cross-section, the larger the overvoltage generated by ferromagnetic resonance, which may cause the PT fuse to blow, and it is more difficult to suppress the resonance by connecting a damping resistor in parallel at the PT open delta. In the planning stage of shale gas field distribution networks, the influence on ferromagnetic resonance should be fully considered while pursuing economic benefits, and the staff need to balance the two factors.

(3) Different fault types will induce resonant overvoltage with different amplitudes. Compared with metallic grounding fault and grounding fault through resistors, the ferromagnetic resonance induced by arc grounding fault is more serious with a larger amplitude. Therefore, efforts should be made to avoid or suppress the occurrence of arc grounding faults and an effective suppression measure should be proposed. In the actual engineering of shale gas field distribution networks, the capacitance to ground should be reasonably controlled to avoid being too large or too small: an excessively large capacitance is prone to induce arc grounding faults, while an excessively small capacitance is likely to trigger high-frequency resonance.

(4) This paper proposes a suppression measure of grounding the high-voltage side of PTs through linear resistors, which can effectively limit the saturation degree of PTs and suppress resonant overvoltage. The feasibility and effectiveness of this method are verified through simulation calculations, which provides a valuable reference for the selection of ferromagnetic resonance suppression measures for the operation and maintenance staff of shale gas fields.

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