Simulation of the pre-magnetization technology for transformer on ship power system

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Abstract. The no-load closing of transformer in the medium-voltage ship power system will cause a large inrush current and threaten the security of the system. This paper aims to provide reference for the pre-magnetization technology of the transformer in medium-voltage ship. Firstly, the basic principles of the inrush current and the series small-capacity transformer based pre-magnetization technology for the transformers are analyzed. Based on the analysis, the typical medium-voltage engineering ship and power generation ship are taken as examples to perform the simulation of the series small-capacity transformer based pre-magnetization scheme, and the result shows that the pre-magnetization technology can suppress the inrush current effectively. Besides, the factors of the switch closing time and the number of generators operating in parallel are considered in the research and their effects of on the inrush current as well as the transient voltage drop are analyzed. Finally, the influence of the pre-magnetization scheme on the differential protection is studied and the operation suggestions are given.

1. Introduction

When the transformer is put into operation with no load, the core flux cannot have an abrupt change and there will be an attenuated flux induced in the winding, which is opposite to the flux produced by the applied voltage. Under this condition, the transformer will work in the DC-bias state and is easy to get into saturation. As a result, the excitation circuit flows in the transformer, or called the inrush current, can reach several times of the rated current.

Compared with the onshore power system, the transformer on the ship power system adopts a compact structure because of the space limitation, and thus the threat of the inrush is more serious. Besides, the inrush current can cause other problems such as voltage drop, harmonics, and malfunction of the protection. Therefore, the suppression of the inrush current of the transformer is the first prerequisite to maintain the security of the ship power system [1].

To this end, various methods have been proposed to suppress the inrush current of the transformer in recent years. Among them, one basic method is to change the impedance of the transformer by changing the structure of the winding. For instance, the research in [2] indicates that the inrush current can be suppressed by changing the YN-connected primary winding into the Zigzag structure. Similarly, the self-inductance of the transformer is increased by changing the winding distribution in [3, 4], and the inrush current can be suppressed to some degree. However, this type of method will increase the transformer volume and manufacturing costs, also it can reduce the operating efficiency. Therefore, it is rarely used in the actual ship power system.
In [5-8], the technology of separate-phase closing used in the onshore power grids is introduced into the ship power system, which determines the optimal closing time by detecting the residual magnetism of the transformer, thus to effectively eliminate the inrush current. Nevertheless, the circuit breaker in the ship power system usually does not have the function of separate-phase closing, and the use of the technology is limited.

Therefore, the most widely used method to suppress the inrush current in the ship power system is the pre-magnetization technology [9-14]. For example, a series resistance based pre-magnetization method is proposed in [12], where a resistor is inserted into the no-load closing circuit of the transformer, thus to limit the inrush current. In [13], the separate-phase closing technology and the series resistor based pre-magnetization are further combined to improve the effect of inrush current suppression. Unfortunately, this method is only suitable for the transformer with YN connected primary winding. In [14], a series small-capacity transformer based pre-magnetization scheme is proposed for low-voltage ship power system, where a small-capacity pre-magnetizing transformer is inserted into the closing circuit of the main transformer, and the pre-magnetizing transformer is closed to the bus first and after a certain delay, the main breaker of the transformer is closed, together with the pre-charged branch removed from the system. The simulation shows that the scheme is more effective than the series resistance based pre-magnetization method in suppress the inrush current, and is more suitable for the ship power systems.

Nevertheless, the existing research for the series small-capacity transformer based pre-magnetization is only suitable for the low-voltage ship, and the problems of the voltage drop and malfunction of the protection are neglected. Therefore, this paper aims at providing reference for the engineering design of the transformer pre-magnetization on the medium voltage ship, and the typical medium voltage engineering ship and power generation ship are taken as the research objects. The comprehensive simulation of the series small-capacity transformer based pre-magnetization scheme is carried out, and the factors such as the switch closing time and the number of generators operating in parallel are considered. Besides, the impact of the pre-magnetization scheme on the transformer differential protection is analyzed.

2. The basic principle of the inrush current

\[ N_1 \frac{d\Phi}{dt} = \sqrt{2}u_1 \sin(\omega t + \alpha) \]  \hspace{1cm} (1)

Where: \( N_1 \), \( \Phi_1 \) represent the turns of the primary winding and the flux of the core; \( u_1 \) is the bus voltage; \( \omega \) represents the angular velocity, and \( \alpha \) is the initial phase angle. If the equation (1) is integrated, the result is
\[ \phi(t) = -\frac{\sqrt{2}u_1}{N_1 \omega} \cos(\omega t + \alpha) + C \]  

(2)

Where \( C \) is the integral constant. Let \( t=0 \), we have

\[ C = \frac{\sqrt{2}u_1}{N_1 \omega} \cos \alpha + \phi_s \]  

(3)

Where \( \phi_s \) is the residual flux of the iron core during the no-load closing state. Substituting equation (3) into equation (2) and considering the attenuation of the DC bias component, the result is

\[ \phi(t) = -\frac{\sqrt{2}u_1}{N_1 \omega} \cos(\omega t + \alpha) + \left( \frac{\sqrt{2}u_1}{N_1 \omega} \cos \alpha + \phi_s \right) e^{-\frac{t}{\tau}} \]  

(4)

Where \( \phi_m = \frac{\sqrt{2}u_1}{N_1 \omega} \), \( \tau \) is the decaying time constant, where \( l \) and \( R \) are the inductance and resistance of the closing circuit.

If the attenuation of the free component is ignored, and \( \alpha = 0, \phi_s = 0.9 \phi_m \), then the flux of the core is determined as shown in Figure.1(b), where the maximum flux is as large as 2.9 \( \phi_m \), and the maximum flux appears at the half cycle after the closing of switch. According to the excitation curve of the transformer, the excitation current will increase rapidly due to the saturation, as shown in Figure.2. Under special condition, the maximum inrush current can be up to hundreds of times of the normal excitation current, and will cause the problems of overheating.

3. Analysis of the series small-capacity transformer based pre-magnetization scheme

The wiring diagram of the series small-capacity transformer based pre-magnetization scheme is shown in Figure. 3(a), where a small-capacity pre-magnetizing transformer, denoted as Pre-T, is connected in series with the main transformer. The Pre-T is first closed to the bus by \( S_2 \), and then the main transformer is charged through the circuit of the Pre-T. In this way, the inrush current of the main transformer can be suppressed by the Pre-T. The closing process of the main transformer can be divided into the following three stages.

The first stage: the switch \( S_2 \) is closed, and the Pre-T is put into operation without load. In this stage, the inrush current is small since the Pre-T has a relatively small capacity.

The second stage: the switch \( S_3 \) is closed and the main transformer is put into operation in series with the Pre-T. Since the stable magnetic flux has been established in the Pre-T, the equivalent circuit of the transformer is as shown in Figure. 3(b). Where \( R_k \) and \( X_k \) represent the short-circuit resistance and reactance of the Pre-T, \( R_1 \) and \( X_1 \) represent the resistance and leakage reactance of the primary winding of T, \( R_m \) and \( X_m \) represent the excitation resistance and reactance of T.
When the switch $S_3$ is closed, the magnitude of the inrush current can be limited due to the function of Pre-T. After a short period, the $R_m$ and $X_m$ of the main transformer will increase to the normal values and a steady-state flux can be established in the winding. The excitation current at this time is:

$$I_0 = \frac{\dot{U}_1}{R_1 + jX_1 + R_1 + R_m + jX_m}$$

(5)

The voltage of the main transformer in the primary winding can be expressed as:

$$\dot{U}_T = \frac{\dot{U}_1[(R_1 + R_m) + j(X_1 + X_m)]}{R_1 + jX_1 + R_1 + R_m + jX_m}$$

(6)

Considering that in steady state, we have:

$$[R_1 + jX_1] \ll [(R_1 + R_m) + j(X_1 + X_m)]$$

(7)

Therefore, the terminal voltage $\dot{U}_T$ of transformer is approximately equal to the applied voltage $\dot{U}_1$. The third stage: the switch $S_1$ is closed, and the switches $S_2$ and $S_3$ is quickly disconnected to remove the pre-magnetization branch. The voltage at the primary winding of $T$ changes from voltage $\dot{U}_1$ to $\dot{U}_1$, the voltage change is very small, and there is almost no inrush current occurred in this stage.

According to the analysis of [14], the capacity of the small-capacity transformer will affect the inrush current at the second stage. When the capacity is small, the inrush current of the main transformer can’t be limited, but the bus voltage is prone to drop greatly. However, if the capacity is chosen too large, the pre-magnetization is unable to get satisfactory results. Therefore, the capacity of the small-capacity transformer is always selected about 5% of the capacity of the main transformer in the practical.

4. Illustrations and simulations

4.1. Simulation of the inrush current without pre-magnetization

4.1.1. Simulation of the transformer on engineering ship. Firstly, the typical medium voltage power system of an engineering ship is taken as an example, and the partial wiring diagram of the system is shown in Figure 4, where the main transformer is a step-down transformer with $\Delta$-$\Delta$ connected windings. The rated capacity of the generator is 5400kVA, the frequency is 50Hz, the rated voltage is 6.3kV, and the power factor is 0.8. The rated capacity of the main transformer is 1500kVA, and the ratio is 6.3kV/400V, the short-circuit impedance is 6%, and the high-voltage side rated current is 137.46A; the pre-magnetizing transformer Pre-T has a rated capacity of 100kVA, the ratio is 6.3kV/6.3kV, and the short-circuit impedance is 6%.
Figure 4. Schematic diagram of the generation unit on the engineering ship.

Figure 5. The amplitude of the three-phase inrush current at different closing times and the curve of maximum inrush current (a) The amplitude of the three-phase inrush current at different closing times (b) The maximum inrush current waveform.

If the pre-magnetizing branch of the system is neglected, the simulation of the inrush current of the main transformer is first implemented, where the complete cycle (4.2s-4.219s) is chosen to perform the closing experiment, and the switch S1 is controlled to close at different times of the cycle, and the curve of the amplitude of the inrush current is shown in Figure.5(a).

As can be seen from Figure. 5, when the S1 is closed at 4.210s, the A-phase inrush current reaches the maximum, and the value is 0.437 kA, which is about 2.253 times the rated current. The waveform of the three-phase inrush current is shown in Figure. 5(b). Besides, when the S1 is closed at 4.215s, the transformer has the minimum inrush current, and the value is 0.119 kA, which is about 0.613 of the rated current.

The transient voltage of the bus is also analyzed and shown in Figure.6. It can be seen that the closing time will influence the voltage drop of the bus. In this cycle, when the closing time is selected at 4.215s, the voltage drop is the most serious and reaches 11.907%, which can threaten the system security.

4.1.2. Simulation of the transformer on generation ship. In order to further simulate the characteristics of the inrush current, the power system of a typical power generation ship is simulated either, and the wiring diagram of the generation unit is shown in Figure.7, where the main transformer is a step-up transformer with Δ-Y connected windings. The rated capacity of the generator in the system is 1250kVA, the frequency is 50Hz, the rated voltage is 630V, and the power factor is 0.8; the rated capacity of the main transformer is 4000kVA, the ratio is 630V/6.3kV, the short-circuit impedance is 6%, and the rated current of the primary winding is 3.66kA; the pre-magnetizing transformer Pre-T has a rated capacity of 200kVA, the ratio is 630V/630V, and the short-circuit impedance is 6%.
Figure 6. The transient voltage drop of the bus at different closing times.

Figure 7. Wiring diagram of a typical power generation ship generating unit.

Figure 8. Inrush current at different closing times and the maximum inrush current waveform (a) The amplitude of the inrush current when \( S_1 \) is closed at different times (b) The curve of the maximum inrush current.

Neglecting the pre-charged branch of the system, the complete cycle (1.2s-1.219s) is chosen to perform the closing experiment. The amplitude of the inrush currents in the experiment is recorded and drawn as shown in Figure 8(a). It can be seen from the figure that when the closing time of \( S_1 \) is selected at 1.215s, the transformer has the maximum inrush current, and the inrush current of phase B can reach 9.61 kA. At this time, the three-phase inrush current is as shown in Figure 8(b).

Similar to the engineering ship, the closing process of the transformer can cause the voltage drop of the bus. In this cycle, when the \( S_1 \) is closed at 1.205s, the voltage drop is the most serious and reaches 9.784%, which will have an impact on the security of the system.

In summary, whether it is a step-up transformer or step-down transformer, there will be a large inrush current and transient voltage drop during the closing process of the transformer. And the magnitudes of the inrush current and transient voltage drop are related to the closing time.
4.2. Simulation of the inrush current with pre-magnetization

4.2.1. Influence of the closing time. Taking the generation ship as an example to simulate the pre-magnetization of the transformer. Since the pre-magnetizing transformer has a small capacity, the inrush current of the Pre-T is relatively small when the switch S2 is closed. Therefore, the inrush current of the main transformer during the closing of S1 and S3 is considered in the simulation. The closing process is considered as follows:

1) To consider the impact of the closing time of S3 individually, the S2 is closed at 0.5s, and the S1 is closed at 1.2s, and the closing time of the switch S3 is chosen to be different (every 0.001s starting from 0.501s). The amplitude of the inrush current in the test is recorded and plotted in the same coordinate system, as shown in Figure.9(a). It can be seen that when the closing time of the switch S3 is selected at 0.511s, the transformer has the smallest inrush current.

2) To consider the impact of the closing time of S1 individually, the S2 is closed at 0.5s, the S3 is closed at 0.511s, and the closing time of the switch S1 is chosen to be different (every 0.001s starting from 1.200s). The amplitude of the inrush current in the test is recorded and plotted as shown in Figure.9(b). When the closing time of the switch S1 is selected at 1.201s, the transformer has the smallest inrush current.

In summary, if the closing time of the switch S2 is 0.5s, the closing time of the switch S3 is 0.511s, and the closing time of the switch S1 is 1.201s, the transformer has the smallest inrush current. Under this condition, the inrush current of the transformer is as shown in Figure. 9(c).

Similarly, if the pre-magnetization branch is considered in the engineering ship, the switch S2 is closed at 0.501s, the S3 is closed at 1.9s, and the S1 is closed at 4.210s. The three-phase excitation inrush current is shown in Figure. 9(d). Form the figure, the maximum value of the inrush current in the first stage is approximately 0.028kA, and the maximum value of the inrush current in the second stage is approximately 0.122kA. Besides, the transient voltage of the bus drops to 4.965kV when the S2 is closed, and the voltage drop percentage is 3.42%. When the S3 is closed, the voltage drops to 4.936kV and the voltage drop percentage is 3.98%. When the S1 is closed, the voltage drops to 5.130kV and the voltage drop percentage is only 0.21%.

Figure 9. Magnetizing inrush current during pre-magnetization and the minimum inrush current waveform (a) Magnetizing inrush current at different closing times of S2 (b) Magnetizing inrush current at different closing times of S1 (c) Combined minimum magnetizing inrush current waveform (d) The smallest three-phase magnetizing inrush current of the engineering ship.
Compared with the results of no pre-magnetization, the maximum amplitude of the inrush current can be limited, and the voltage drop of the bus in each stage is limited to 5% or less. The results show that pre-magnetization technology has satisfied effect to suppress the inrush current.

4.2.2. Influence of the number of generators operating in parallel. For power generation ship, there can be multiple generators in parallel in one generation unit. The influence of the operating state of generators is simulated in this section.

1) Pre-magnetization with single generator. Considering that there is only one generator operating in the model, the closing time points of $S_2$, $S_3$, and $S_1$ are selected as 0.16s, 0.26s and 0.36s, and the inrush current of the transformer and the voltage of the bus are as shown in Figure. 10.

![Figure 10](image1)

(a) Inrush current and bus voltage with single generator (b) Three-phase inrush current (b) Voltage of the bus.

It can be seen from Figure. 10 that the maximum value of the inrush current is 0.151kA when the switch $S_3$ closed, and the voltage drop is 14.08% (the amplitude of the voltage is about 0.433kV). When the switch $S_1$ is closed, the maximum value of the inrush current is 0.184kA, and the voltage drop is 5.13% (the amplitude of the voltage is about 0.462kV).

2) Pre-magnetization with three generators in parallel. Considering that there are three generators operating in parallel in the model, the closing time points of the switches are the same as above, and the inrush current of the transformer and the voltage are as shown in Figure. 11.

![Figure 11](image2)

(a) Inrush current and bus voltage with three generators (a) Three-phase inrush current (b) Voltage of the bus.

Under this condition, the maximum value of the inrush current is 0.191kA when $S_1$ closed, and the voltage drop is 3.81% (the amplitude of the bus voltage is about 0.480kV). When the switch $S_1$ is closed, the maximum value of the inrush current is 0.258kA, and the voltage drop is 2.00% (the amplitude of the voltage is about 0.489kV).

It can be seen from the comparison of the above two conditions that when the generator is operated alone, the inrush current is relatively small, but the voltage drop of the bus cannot meet the demand of security. However, the mode of multiple generators running in parallel helps to maintain voltage level, and the inrush current does not increase significantly, therefore it is beneficial for the safe operation of the system.
4.3. The influence of pre-magnetization on the differential protection

The starting current of the transformer differential protection is generally set to 0.2 to 0.5 times of the rated current. According to the above simulation, the inrush current of the transformer can be limited to 0.65kA (about 0.178 times of the rated current) when the pre-magnetization technology is used, which is less than the starting current of the differential protection. Therefore, the differential protection of the transformer will not malfunction during the process of pre-magnetization.

Figure 12. Inrush current during the fault removing process (a) The three-phase inrush current waveform (b) The curve of the second harmonic ratio.

However, considering that the inrush current of the transformer is not only generated during the no-load closing process, but also during the removing process of the external fault. To simulate this scenes, a three-phase short-circuit fault is set on the outlet line of the transformer. The fault occurs at 2.495s and the fault duration is 0.5s. The inrush current generated in the transformer during the fault recovery process is shown in Figure.12(a). It can be seen that the maximum value of the inrush current is 4.528kA, which is greater than the starting current of the transformer differential protection, and the protection may be malfunctioned.

In engineering, the second harmonic is usually used to prevent malfunction of the differential protection caused by the inrush current. If the second harmonic ratio of the differential current of the transformer is greater than the setting values (generally 15% to 20%), then the differential protection is blocked. Therefore, the second harmonic component of the restorative inrush current is analyzed as shown in Figure. 12(b). It can be seen that during the fault recovery process, the maximum value of the second harmonic ratio is about 41%, which exceeds the setting value. Therefore, the second harmonic based blocking criterion of the differential protection still needs to be put into operation, thus to effectively prevent the malfunction of the transformer differential protection.

5. Conclusion

The suppression of the inrush current of the transformer on the ship power system is of great significance for the system security. In this paper, the basic principles of the inrush current of the transformer and the series small-capacity transformer based pre-magnetization technology are analyzed. Based on these analyses, the pre-magnetization simulations of the medium-voltage ship power systems are carried out. The simulation results show that whether it is for the engineering ship or generation ship, the inrush current and bus voltage drop can be suppressed by controlling the closing time, but the closing time is difficult to select. The series small-capacity transformer based pre-magnetization technology can effectively reduce the impact of the inrush current on the transformer and improve the safety of the system even when the switch is closed at the worst time. Besides, the mode of multiple generators running in parallel helps to maintain the bus voltage without increasing the inrush current significantly. In addition, the restorative inrush current can cause the malfunction of the differential protection, and the second harmonic based blocking criterion should be used. The research in this paper can provide reference for the design of the ship medium voltage power system.
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