Research on Operating Conditions of Electric Propulsion Ships under Transformer Interturn Short Circuit

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Abstract. Most ships currently use electric propulsion systems. In this system, the transformer plays a key role in power distribution. The probability of interturn short circuit occurs in the transformer is high, it will cause faults such as three-phase voltage imbalance and endanger the safe operation of the ship. The simulation model of ship electric propulsion system established in this paper includes propellers and transformers, and the influence of the interturn short circuit of a transformer on the sailing conditions is studied. The research results show that the transformer interturn short circuit will generate a huge inrush current and have a huge impact on the torque and speed of the propeller.

1 Introduction

Failure of ship power system has bad influence on propulsion system. Transformers are the key distribution equipment in the ship’s power system. Interturn short-circuit faults of transformers, as a common fault, can cause huge current fluctuations and unbalance of three-phase voltages, which seriously affect the ship’s operating conditions[1]. At present, it is hard to find realted research of the influences of transformer interturn short circuit on the ship operating conditions, so its of great significance to carry out the research.

2 Modeling of ship electric propulsion system

2.1 Brief introduction of ship electric propulsion system

This paper takes a typical medium-voltage exploration ship(1000V~ 10kV) as an example to comprehensively model its electric propulsion system, and focuses on the establishment of the transformer interturn short circuit model and the propeller load model. The ship electric propulsion system is an integrated system connected in a certain way by power generation equipment, power distribution equipment, power network and propulsion systems and load equipment and propeller loads. It is the overall system on the ship, which has all the equipment responsible for the generation, transmission, distribution and use of electrical energy.[2]. The system structure is shown in Fig1.
2.2 Transformer interturn short circuit Modeling

A transformer is a device that uses the principle of electromagnetic induction to change AC voltage[3]. This paper chooses the most common Yyn0 type transformer for simulation research. The characteristics of the transformer are related to resistance and magnetic leakage, which are usually represented by "T" type equivalent circuits, as shown in Fig 2.

Using the equivalent circuit method to model, its mathematical model is as follows: The circuit expression is

\[
\begin{align*}
  i_1 &= \frac{\psi_1 - \psi_{sat}}{x_{1m}} \\
  i_2 &= \frac{\psi_2 - \psi_{sat}}{x_{2m}} \\
  i_3 &= \frac{\psi_3 - \psi_{sat}}{x_{3m}}
\end{align*}
\]

(1)

In the formula, \(i_1, i_2, i_3\) represent the primary and secondary current values of the transformer and transformer fault phase current; \(\psi_1, \psi_2, \psi_3, \psi_{sat}\) represent the primary magnetic flux, the secondary magnetic flux, the fault turn flux and the main magnetic flux;
\( x_{1\sigma}, x_{2\sigma} \) represent the primary and secondary impedance values; the saturation value of the magnetic flux is used to represent the current value of the primary and secondary windings.

The main flux can be expressed as:

\[
\psi_m^{sat} = x_{1\sigma} \left( \frac{\psi_{1}}{x_{1\sigma}} + \frac{\psi_{2}'}{x_{2\sigma}} - \frac{\Delta \psi}{x_{m1}} \right) 
\]

The magnetic flux state variable expression is:

\[
\psi_{1} = \int \left[ \omega_{1} U_{1} - \omega_{1} r_{1} \left( \frac{\psi_{1}'}{x_{1\sigma}} - \frac{\psi_{2}'}{x_{2\sigma}} - \frac{\Delta \psi}{x_{m1}} \right) \right] dt \\
\psi_{2} = \int \left[ \omega_{2} U_{2} - \omega_{2} r_{2} \left( \frac{\psi_{1}'}{x_{1\sigma}} - \frac{\psi_{2}'}{x_{2\sigma}} - \frac{\Delta \psi}{x_{m1}} \right) \right] dt \\
\psi_{3} = \int \left[ \omega_{3} U_{3} - \omega_{3} r_{3} \left( \frac{\psi_{1}'}{x_{1\sigma}} - \frac{\psi_{2}'}{x_{2\sigma}} - \frac{\Delta \psi}{x_{m1}} \right) \right] dt
\]

2.3 Propeller modeling

Considering the excellent dynamic and static performance required by the propeller, this paper uses a double-fed motor to simulate the propeller load[5]. Its basic mathematical model is as follows:

The voltage equation is:

\[
\begin{bmatrix} U_{qp} \\ U_{qc} \\ U_{sp} \\ U_{sc} \\ U_{dp} \\ U_{dc} \end{bmatrix} = \begin{bmatrix} r_{p} + L_{sp} p & P_{p} L_{sp} \omega_{r} & 0 & 0 & 0 & 0 \\ -P_{p} L_{sp} \omega_{r} & r_{p} + L_{sp} p & 0 & 0 & 0 & 0 \\ 0 & 0 & r_{p} + L_{sp} p & 0 & 0 & 0 \\ 0 & 0 & 0 & r_{p} + L_{sp} p & 0 & 0 \\ M_{p} & 0 & 0 & 0 & r_{p} + L_{sp} p & 0 \\ 0 & M_{p} & 0 & 0 & 0 & r_{p} + L_{sp} p \end{bmatrix} \begin{bmatrix} i_{qp} \\ i_{qc} \\ i_{sp} \\ i_{sc} \\ i_{dp} \\ i_{dc} \end{bmatrix}
\]

The electromagnetic torque equation is:

\[
T_{e} = T_{sp} + T_{in} = P_{p} M_{p} \left( i_{qp} i_{dp} - i_{qp} i_{dp} \right) + 4 P_{p} M_{c} \left( i_{sp} i_{dp} + i_{sc} i_{dc} \right)
\]

The equation of motion is:

\[
T_{e} - T_{m} = \frac{J d \omega}{p} dt
\]

In the formula, \( p, L_{sp} \) and \( R_{p} \) are number of pole pairs in power winding, self-inductance, resistance; \( p, L_{pc} \) and \( L_{sc} \) are number of control pole pairs, resistance, self-inductance and mutual inductance between control winding and rotor; \( R_{r} \) is rotor resistance, rotor self-inductance; \( M_{p}, M_{c} \) are mutual inductance between power winding and rotor, mutual inductance between control winding and rotor; \( \omega_{r} \) is mechanical angular speed of the motor; \( U_{qp}, U_{dc}, U_{qc}, U_{qr}, U_{sp}, U_{sc}, i_{qp}, i_{dp}, i_{dc}, i_{sc}, i_{qr}, i_{dc}, i_{dc}, i_{qr}, i_{dc}, i_{dc}, i_{qr} \) both represent transient values of voltage and current. \( T_{e}, T_{p}, T_{c} \) are electromagnetic torque and load torque. \( T_{sp}, T_{ec} \) are torque of power winding and control winding. The subscripts \( p \) and \( c \) represent the power winding and the control winding, and the subscripts \( s \) and \( c \) represent the stator side and the rotor side; the subscripts \( q \) and \( d \) represent the axial components of the d-q axis, and \( p \) is a differential operator. According to the above basic equation, the corresponding propeller load model can be established in MATLAB.
In summary, the model of the ship's electric propulsion system is shown in Figure 4.

Figure 4. Simulation model of ship's electric propulsion system.

3 Simulation analysis of typical working conditions

This paper uses the ship sailing conditions as an example to analyze the ship's operating conditions under transformer fault conditions. The ship set sail using three-stage acceleration, the rated maximum speed of the propulsion motor is 1000r/min, and takes 0.2 times reduction gear to propeller. Here, 40%, 80%, and 100% of the maximum speed are used for stepwise acceleration. The given speed signal is: 0~2s speed from static start to 80r/min, 2~4s to 160r/min, 4~6s to 200r/min. When accelerating, use uniform acceleration to a certain speed for 1s and then continue to accelerate uniformly. Simulate the interturn short circuit of the transformer, set the transformer to fail at 3s, and use the propeller speed and torque to represent the ship's operating conditions.

3.1 Simulation of ship operating conditions under transformer interturn short circuit

Simulate the operating conditions in this state, the simulation results are as follows: Fig 5 shows voltage and current waveforms of the secondary side of the transformer during the interturn short circuit of the transformer during the sailing phase; Fig 6 shows transformer interturn short circuit propeller speed and torque.

Figure 5. Interturn short circuit transformer secondary side voltage and current waveform.
Figure 6. Transformer interturn short circuit propeller speed and torque.

Analysis shows: when the transformer has an interturn short circuit, there will be an instantaneous current surge process on the secondary side, and a stable sine wave will be reached after a large current surge of about 0.2s. The stabilized sine wave current is about 5 times higher than the normal operating current. The big current may damage the transformer. In 2.25s after the interturn short circuit, the propeller speed was reduced from 125r/min to -200r/min and accompanied by a speed fluctuation of about 50 revolutions. At the moment of short circuit, a large negative value of torque appears, followed by huge positive and negative fluctuations, and the propeller reverses or stalls.

4 Conclusion

A comprehensive analysis of the ship's sailing conditions under the condition of a transformer interturn short circuit can be obtained: When the transformer has an interturn short circuit, its short-circuit current is large, and the peak value of the shock reaches 2800A. The speed and torque of the propeller have huge disturbances, and its operation is completely inconsistent with the signal given by the frequency conversion system, which is extremely harmful to the propeller and other equipment. Therefore, the resistance of the propulsion motor shaft needs to be improved, and an overcurrent protection device should be installed at the inverter side.

References

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