The Study of Residual Voltage of Induction Motor and the Influence of Various Parameters on the Residual Voltage

Shuping Zhang\textsuperscript{1}, Chen Zhao\textsuperscript{1} and Weipu Tan\textsuperscript{1}

\textsuperscript{1} North China Electric Power University, School of Electrical & Electronic Engineering, Flexible Power Technology Institute, Changping, Beijing, 102206, China

463466516@qq.com, 17801150306@163.com, tanweipu@ncepu.edu.cn

ABSTRACT: The majority important load of industrial area is mainly composed of induction motor, it is more common that induction motor becomes sluggishness and even tripping due to the lose of power supply or other malfunction in the practical work. In this paper, space vector method is used to establish a reduced order model of induction motor, and then study the changes of motor electromagnetic after losing electricity. Based on motion equations of the rotor and magnetic flux conservation principle, it uses mathematical methods to deduce the expression of rotor current, rotor flux, the stator flux and the residual voltage of stator side. In addition, relying on thermal power plants, it uses the actual data of power plants, takes Digsilent software to simulate the residual voltage of motor after losing electricity. analyses the influence on the residual voltage with the changes of the moment of inertia, load ratio, initial size of slip and the load characteristic of induction motor. By analysis of these, it has a more detailed understanding about the changes of residual voltage in practical application, in addition, it is more beneficial to put into standby power supply safely and effectively, moreover, reduce the influence of the input process to the whole system.

1. Introduction

With the rapid development of large capacity generator unit, supply reliability of the plant-power is required higher and higher. Security and reliability of plant-power system are related to the unit and safety of power plant, even is associated with the safe operation of the whole system. The thermal power plant load is mostly induction motor, and for large induction motor, the magnetic energy and inertia are large. And its winding resistance is much smaller than the leakage resistance, so the bus residual voltage and current decay slowly, which will influence the bus even after several seconds. In practical application, appearance of malfunction is inevitable. And it is common that the event of a power outage would lead to tripping of induction motor at a moment. In order to maintain the magnetic energy of the motor does not jump, an instantaneous induced current will appear in the rotor loop. It offsets magnetic flux changes caused by the loss of stator current. Therefore, the flux is not mutational. This current is attenuated by the time constant of the rotor windings, which produces a magnetic field that rotates at the rotor speed relative to the stator windings. The rotating magnetic field induces an electromotive force in the stator winding, which is what we usually call the residual voltage of the induction motor. If the standby power supply is not put in at the right time, an impact will occur due to the residual voltage. If the standby power is put into at the reverse phase, the inrush current can reach 20 times of the rated current. The inrush current is so large that may lead to a certain degree of damage of the equipment and produce a lot of electromagnetic interference, which will affect the...
normal operation of other electrical equipment within the power grid, and will cause the bus voltage sag, easily lead to the action of system route protection, resulting in the failure of switching operation. So, it is necessary to analysis residual voltage, and its changes in the process, as well as the impact on the residual voltage caused by changes of some parameters.

2. Model of induction motor

Schematic diagram of Three-phase induction motor has been shown in Figure 1. Three-phase stator winding is represented by ABC and three-phase rotor winding is represented by abc. According to the motor model convention, the positive direction of the motor rotor rotates along counterclockwise from A to B, as is indicated by the arrow in the figure. $\theta$ is the angle between A-phase winding axis of the stator and a-phase winding axis of the rotor. Stator and rotor of three-phase induction motor have symmetrical parameters and uniform air gap[1]. To eliminate the time-varying coefficients in the flux and voltage equations, the rotor-side parameters are transformed into the stator coordinate system. In this paper, the space vector method is used to represent the three-phase variables, simplifying the motor model and numerical analysis and calculation, making the analysis easier to understand.

![Figure 1. Flexible direct current transmission principle](image1)

![Figure 2. Instantaneous value and the synthesis space vector of rotor three-phase voltage](image2)

The transform matrix of the specified space vector coordinate system to the abc coordinate system is as follows:

$$T = \frac{1}{2} \begin{bmatrix} 1 & 1 & 2 \\ \alpha^2 & \alpha & 2 \\ \alpha & \alpha^2 & 2 \end{bmatrix}$$  \hspace{1cm} (1)

Similarly, The transform matrix of the abc coordinate system to the specified space vector:

$$T^{-1} = \frac{2}{3} \begin{bmatrix} 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$  \hspace{1cm} (2)

Assuming that the instantaneous values of the three-phase voltage are $u_a, u_b, u_c$, the space vector of the voltage obtained by the above transformation matrix is:

$$u = \frac{2}{3} (u_a + \alpha u_b + \alpha^2 u_c)$$  \hspace{1cm} (3)

Here, $\alpha = e^{j120^\circ}$ is a unit complex vector or a spatial operator whose phase angle is 120. Similarly, $\alpha = e^{j240^\circ}$ is a unit complex vector or a spatial operator with a phase angle of 240°. $|u|$ represents the modulo value of the voltage. Instantaneous value[2] and the synthesis space vector of rotor three-phase voltage are shown in Fig.2.
Similarly, the voltage and the flux can also be expressed in the form of space vector, so that the motor model and numerical operations are simplified.

As is shown in Fig. 1, when stator windings of squirrel cage induction motor adopts star connection method, rotor adopts star connection method equivalent, the induction motor is expressed by the space vector, the voltage and flux linkage equations of the stator and rotor are established as follows:

$$
\begin{align*}
    u_s &= R_s \dot{i}_s + p \dot{\psi}_s \\
    0 &= R_s \dot{i}_s + (p - j\omega_p) \dot{\psi}_s \\
    \psi_s &= L_s \dot{i}_s + M_{sr} \dot{j}_r \\
    \dot{\psi}_s &= M_{sr} \dot{i}_s + L_s \dot{i}_r
\end{align*}
$$

(4)

Here, $u_s$, $\dot{i}_s$, $\dot{\psi}_s$ denote respectively stator voltage, stator current and stator flux linkage. $\dot{i}_r = \hat{i}_r e^{j\theta}$, $\psi_r = \psi_r e^{j\theta}$, $\dot{i}_r$, $\dot{\psi}_r$ denote, respectively, the rotor current and rotor flux linkage in the complex coordinate system of the rotor. $\omega_p$ is angular frequency of the rotor voltage; $p$ is a time differential operator and $p = \frac{d}{dt}$.

3. Analysis of residual voltage of induction motor

After the loss of power of the stator side of the induction motor, the rotor side current expression can be obtained according to the magnetic flux conservation principle. And the residual voltage of the induction motor is deduced. The rotor winding of the induction motor is usually short-circuited, which means the rotor voltage is zero.

$$
u_s = R_s \dot{i}_s + L_s \frac{d\dot{i}_s}{dt} = 0
$$

(5)

Stator current becomes zero after the power failure. Because the flux linkage can not jump, Initial value of rotor current can be obtained. The rotor current after the power failure time can be expressed as:

The rotor current converted to the stator side is:

$$
\dot{i}_s = \hat{i}_r e^{j\theta} = \hat{i}_{r0} e^{\frac{t_0 - t}{\tau_r}} e^{j\theta}
$$

(6)

Where $\tau_r = \frac{L_r}{R_r}$ is the rotor circuit time constant, $t_0$ is the power-off time, $\theta = \omega_0 t + \theta_0$ is the angle of corresponding phase of rotor and stator. $\theta_0$ is the angle at the moment of power failure.

The torque equation of the motor is:

$$
T_e = \frac{3}{2} \rho_p \hat{\psi}_s \times \hat{i}_s = T_L + R_\Omega \Omega + J \frac{d\Omega}{dt}
$$

(7)

Here, $T_e$ and $T_L$ denote respectively electromagnetic torque and load torque of the motor. $R_\Omega$ is the motor rotation resistance coefficient. $J$ is the moment of inertia. At the moment of power failure, the electromagnetic torque becomes 0, so the motor torque equation is $T_e = 0$. Assume the load torque $T_L$ and angular velocity $\Omega$ are of a linear relationship:

$$
T_L = T_{L0} + R_\Omega \Omega
$$

(8)

The solution of rotor angular velocity is:

$$
\Omega = \Omega_0 e^{\frac{t-t_0}{\tau_r}} - \frac{T_{L0}}{R_\Omega + R_\Omega} (1 - e^{\frac{t-t_0}{\tau_r}}) \quad t \geq t_1
$$

(9)

The change rule of rotor angle is:
\[ \theta = \theta_1 + \int_{t_1}^{t} \Omega dt \quad t \geq t_1 \]  

(10)

\[ \theta_1 \] is the rotor angle when \( t = t_1 \). The stator current becomes zero after the loss of power, so:

\[ u_s = \frac{d\hat{\psi}_r}{dt} \]

(11)

\[ \frac{d\hat{\psi}_r}{dt} = (L_r - \frac{M_r^2}{L_e}) \frac{di}{dt} + j\omega_r M_r^2 \hat{I}_r + \left( j\omega_r - \frac{1}{T_r} M_r \right) I_m \]

Therefore, the stator voltage[5] is:

\[ u_s = M_m \hat{I}_m e^{-\frac{t-t_0}{T_r}} (j\omega_r - \frac{1}{T_r}) e^{j\phi} \]

(12)

In a word, the amplitude of stator residual voltage[6] is determined by the rotor speed and the rotor current. The amplitude of stator residual voltage decays with the rotor time constant, and the rotor current decays also according to the rotor winding time constant[7]. The frequency of residual voltage is determined by the rotor speed.

4. Influence of parameters on residual voltage of induction motor

In this paper, an integrated power system calculation software package named Digsilent is used to establish a simulation model. DiGILENT 7 is the world's first integrated graphical interface software with single-line diagram for power system analysis, including drawing, editing and all the relevant static and dynamic computing functions. As shown in Fig. 3, in the plant-power supply system, the generator capacity is 1000MW. The export voltage is 27kV. The main transformer capacity of the power plant is 1170MVA, and its variable ratio is 27/530 ± 2 × 2.5% kV. The main transformer capacity is 70/40-40MVA, and its variable ratio is 27/10 ± 2 × 2.5% kV. The external network system voltage is 500kV. The rated voltage of the motor connection busbar is 10kV.

![Figure 3. Single line figure of the plant-power system](image)

Table 1 shows the induction motor model parameters. In the following text, we will analyze the inertia size, load ratio, slip size of the residual voltage of the induction motor[8]. Changing one parameter of the induction motor only, other parameters remain the same, to observe the residual Pressure amplitude and phase angle change curve.

| Motor | V(kV) | P(MW) | S (%) | Initia(kg·m²) | Loading (%) |
|-------|-------|-------|-------|--------------|-------------|
| M1    | 10    | 1     | 0.47  | 46.981       | 100         |
| M2    | 10    | 1     | 0.47  | 35           | 100         |
| M3    | 10    | 1     | 0.47  | 46.981       | 100         |
| M4    | 10    | 1     | 0.47  | 46.981       | 50          |
| M5    | 10    | 1     | 0.47  | 46.981       | 100         |
| M6    | 10    | 1     | 3.33  | 46.981       | 100         |
Figure 4. Amplitude and phase angle of residual voltage of induction motor after changing inertia.

From Fig 4, it can be seen that greater inertia leads to slower rate of descent of amplitude and phase angle of residual voltage.

Figure 5. The amplitude and phase angle of residual voltage of induction motor after changing the load rate.

From Fig 5, it can be seen that induction motor with smaller load has slower rate of descent of amplitude and phase angle of residual voltage.

Figure 6. The amplitude and phase angle of residual voltage of induction motor after changing slip.

From Fig 6, the size of the rated slip of the induction motor has little effect on residual voltage [9].

The induction motor has linear and non-linear load. Table 2 shows the curve parameters of linear load and non-linear load, where load of M8 is linear and that of M7 is non-linear.

Table 2. The curve parameters of induction motor.

| SM  | Mechanical load curve parameters |  
|-----|----------------------------------|  
|     | alfp  | slipm  | exp1   | alfp  | exp2   | xkm   |
|-----|--------|--------|--------|--------|--------|-------|
| M7  | 1      | 0.86   | 1.728  | 0.11   | 3.2    | 0.045 |
| M8  | 1      | 0.86   | 1      | 0      | 1.14   | 0.14  |

To simulate the influence of the difference between the load type on the residual voltage curve, the total simulation time is set to 5s. Induction motor operate normally before t=1s. Power failure occurs at t=1s. The waveform is shown in Figure 7.

Figure 7. Residual amplitude and phase angle of induction motors of different load types.
From the analysis of Fig. 7, it can be seen that the induction motor of different load type has different rate of descent of residual voltage. The amplitude and phase angle of the residual voltage of induction motor with linear load are faster in the rate of descent than that of non-linear load induction motor.

Because the induction motor is the main load which results in changes of residual voltage, and the process of residual voltage changes has great effect on the switching process of backup power supply, even plays a key role in whether the standby power supply can succeed during switching process. Put the stator residual voltage of the induction motor on the theoretical and simulation analysis. By analyzing the parameters, we can see the process of how each parameter influences the residual voltage. Combined with different load types, different load rate, we can have a general judgment on residual voltage. For example, induction motor of low load rate or with non-linear load has lower changing rate of residual voltage. In the same circumstances, it may be more conducive to the input of standby power.

5. Summary
In this paper, space vector method is used to establish a reduced order model of induction motor, which simplifies the numerical calculation and makes the physical meaning more clear. According to the theory of magnetic chain conservation, the change of rotor current and stator residual voltage during the process of loss of power is deduced. And the parameters affecting residual voltage are analyzed theoretically. At the same time, using DigSILENT software, based on actual power plant data, a model of plant power system is built. Controlling variable method was adopted as an approach to analyze how inertia, load proportion, and initial slip of induction motor, as well as variation of load type influence on the stator residual voltage of induction motor. From the simulation, it can be seen that greater inertia leads to slower rate of descent of amplitude and phase angle of residual voltage, induction motor with smaller load has slower rate of descent of amplitude and phase angle of residual voltage. The size of the rated slip of the induction motor has little effect on residual voltage. The amplitude and phase angle of the residual voltage of induction motor with linear load are faster in the rate of descent than that of non-linear load induction motor. Through the analysis above, we have a deeper understanding of residual pressure, which makes us more conducive to the input of standby power in the actual project.

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