Postprint: Fault Simulation Analysis of Mining Three-Phase Induction Motors

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Abstract

Three-phase asynchronous motors constitute the primary power equipment in coal mine production. Over 90% of motor failures result from operation under abnormal conditions, with the main causes including grounding, locked rotor, phase loss, three-phase voltage imbalance, overload, and short circuit faults. Operation in such abnormal states leads to excessive stator current, which causes reduced motor lifespan and insulation aging under prolonged operation, and may severely result in motor burnout. Therefore, investigating the various operating states of motors and analyzing current and voltage characteristics under abnormal conditions constitute the foundation for accurate fault diagnosis and appropriate protection implementation. The traditional approach to analyzing three-phase asynchronous motors involves establishing differential equations based on the motor' s mathematical model, followed by solving and simplifying calculations using numerical analysis methods. This paper utilizes the SimpowerSystems toolbox in Matlab software to analyze the operating states of three-phase asynchronous motors and performs simulation analysis of typical faults including short circuit, overload, locked rotor, and phase loss.

Full Text

Mine Three-Phase Asynchronous Motor Fault Simulation Analysis

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Abstract

Three-phase asynchronous motors serve as the primary power equipment in coal mine production. Over 90% of motor damage results from abnormal operation, commonly caused by faults such as grounding, locked rotor, phase loss, three-phase voltage imbalance, overload, and short circuits. Operating under these abnormal conditions leads to excessive stator current, which reduces motor lifespan and accelerates insulation aging, potentially causing motor burnout. Therefore, analyzing motor operating states and identifying current and voltage characteristics under fault conditions is fundamental to accurate fault diagnosis and effective protection. Traditional analysis methods for three-phase asynchronous motors involve creating differential equations based on mathematical models and solving them using numerical analysis techniques. This paper employs the SimPowerSystems toolbox in Matlab to analyze motor operating states and simulate typical faults including short circuits, overload, locked rotor, and phase loss.

Keywords: Three-phase asynchronous motor; Matlab; fault analysis

1 Introduction

Electric motors are widely used power equipment in mine production. With increasing coal output and mechanization, the number and power rating of motors employed in production continue to grow. Due to the exceptionally harsh operating environment in coal mining, electromechanical equipment experiences severe damage and high failure rates. Motor faults directly impact safe production in coal mines, accounting for over 60% of underground electromechanical accidents and significantly affecting both safety and economic efficiency [2].

2.1 Overview of Mine Three-Phase Asynchronous Motors

Motors constitute the primary power source in coal production, with various types employed in mines. Based on power supply characteristics, they can be classified as DC or AC. DC motors are less common in coal production, mainly used in mine hoists and electric locomotives. Three-phase asynchronous motors are most widely used in coal mine applications, as shown in Figure 1 [Figure 1: see original paper]. These motors offer high efficiency, simple structure, and no contact points between rotating and stationary parts except for bearings at both ends, making them easy to manufacture with explosion-proof structures. They also provide good starting and overload performance with smooth torque characteristics [3]. Consequently, most motors in coal mines adopt three-phase asynchronous AC design, and this study focuses on simulation for protection of such mine-duty motors.

2.2 Mathematical Model of Mine Three-Phase Asynchronous Motors

As the primary power source in coal production, mine three-phase asynchronous motors can be modeled under the following assumptions for this study:

1. Power system harmonics are neglected, and motor stator and rotor windings are assumed to be perfectly symmetrical (spatially displaced by 120°,

as shown in Figure 2 [Figure 2: see original paper]), with uniform air gap and sinusoidal magnetomotive force.
2. Winding impedance values remain constant, with fixed self and mutual inductance coefficients.
3. Iron core losses are not considered.
4. External factors such as temperature and frequency variations are ignored.

The mathematical model for mine explosion-proof three-phase asynchronous motors in the d-q coordinate system is as follows:

Voltage Equations:

$$U_{ds} = R_s i_{ds} + p\psi_{ds} \tag{1}$$
$$U_{qs} = R_s i_{qs} + p\psi_{qs} \tag{2}$$
$$U_{dr} = R_r i_{dr} + p\psi_{dr} + \omega_r L_m i_{qs} - \omega_r L_r i_{qr} \tag{3}$$
$$U_{qr} = R_r i_{qr} + p\psi_{qr} - \omega_r L_m i_{ds} - \omega_r L_r i_{dr} \tag{4}$$

Flux Linkage Equations:

$$\psi_{ds} = L_{ls} i_{ds} + \psi_{dm} = L_s i_{ds} + L_m(i_{ds} + i_{dr}) \tag{5}$$
$$\psi_{qs} = L_{ls} i_{qs} + \psi_{qm} = L_s i_{qs} + L_m(i_{qs} + i_{qr}) \tag{6}$$
$$\psi_{dr} = L_{lr} i_{dr} + \psi_{dm} = L_r i_{dr} + L_m(i_{ds} + i_{dr}) \tag{7}$$
$$\psi_{qr} = L_{lr} i_{qr} + \psi_{qm} = L_r i_{qr} + L_m(i_{qs} + i_{qr}) \tag{8}$$

Electromagnetic Torque and Mechanical Torque Equations:

$$T_e = N_p(\psi_{dr} i_{qs} - \psi_{qr} i_{ds})$$

$$T_e - T_L = J\frac{d\omega_r}{dt}$$

The dynamic model represents a strongly coupled, multivariate, high-order nonlinear power system [3]. This simulation is based on the three-phase asynchronous motor dynamic model. Due to the complexity of this model with numerous variables and high order, the above assumptions are made to simplify the mathematical model for this study.

3 Simulink Simulation of Short-Circuit Faults

Coal mining and tunneling operations generate substantial amounts of coal dust, gas, and other flammable and explosive mixtures. The complex and variable geological conditions require mine three-phase asynchronous motors to have explosion-proof capabilities. Most mine motors are mobile, operating in damp conditions with ambient temperatures constrained by mine ventilation systems.

Their faults exhibit unique characteristics compared to conventional three-phase asynchronous motors, with different features depending on the application. For example, shearer motors do not consume constant power; rather, power consumption varies with coal seam structure. Rock inclusions in coal seams cause load fluctuations, occasional overloads, severe vibrations, and potential locked-rotor conditions. Consequently, overload and locked-rotor faults are common in shearer motors. Similarly, scraper conveyors typically use single-speed or two-speed motors that often start under load, resulting in frequent starting faults [4].

3.1 Motor Parameter Selection

This design selects the YX3E-5 three-phase asynchronous motor manufactured by Nanyang Explosion-Proof Motor Group. Detailed parameters are listed in Table 1 .

3.2 Building the Simulink Model

The short-circuit fault simulation model for three-phase asynchronous motors is shown in Figure 3 [Figure 3: see original paper]. The model utilizes components from the SimPowerSystems toolbox to represent the three-phase source, voltage and current measurements, asynchronous machine, and fault simulation elements.

3.3 Short-Circuit Fault Analysis

Short-circuit faults occur when supply lines make direct or indirect metallic contact with earth or contact through small impedance, causing motor short circuits. These include phase-to-phase and inter-turn short circuits. Such faults result from excessive current, large supply voltage fluctuations, single-phase operation, mechanical damage, or poor manufacturing that damages insulation. Specific types include inter-turn, inter-coil, inter-pole, and inter-phase short circuits. Mine three-phase asynchronous motors frequently operate under high load, making short-circuit faults particularly common.

Simulation focuses on short-circuit faults under ungrounded neutral conditions. Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper] show waveforms for two-phase short-circuit faults, with the fault period from 0.1 to 0.6 seconds. Analysis of simulation results during the fault period reveals: asymmetric three-phase stator currents with significant negative-sequence components, sudden current magnitude increases, and asymmetric three-phase impedance. The faulted phase exhibits lower impedance than healthy phases, potentially causing rotor instability during continued operation.

For effective two-phase short-circuit prevention considering the special mine environment, regular motor maintenance is essential. Large equipment should have backup units to avoid prolonged high-load operation of a single motor, allowing alternating operation between primary and backup equipment. Additionally, power supply quality must be improved to reduce voltage fluctuations and frequency deviations.

Three-phase short-circuit current and electromagnetic torque waveforms under ungrounded neutral conditions are shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper], with the fault period from 0.1 to 6 seconds. The three-phase short-circuit current is calculated as:

$$I_p = \frac{3U_{ap}}{Z_{K\Sigma}}$$

Although three-phase short-circuit faults have low probability, their consequences are extremely severe. Here, I_p is the short-circuit current, U_{ap} is the average voltage at the fault location, and $Z_{K\Sigma}$ is the total impedance in the fault loop. Theoretical calculation yields a short-circuit current of approximately 0.235 A, while the simulation shows a maximum current of 0.286 A (RMS value 0.203 A), resulting in an error of 0.036 A between simulation and theoretical calculation.

Simulation results demonstrate that short-circuit faults generate powerful inrush currents that continue increasing, producing substantial heat that can burn equipment and cause major fires or injuries. In high-gas mine environments, this heat can indirectly trigger gas explosions, seriously threatening workers' lives.

4.1 Building the Matlab Simulation Model

Using components from the SimPowerSystems toolbox in Matlab, a Simulink simulation model is established [5], as shown in Figure 8 [Figure 8: see original paper]. Appropriate parameters are entered for each model component.

4.2 Overload Operation Analysis

Overload in three-phase asynchronous motors occurs when current exceeds the rated value for an allowable period. Overload capacity is defined as the ratio of maximum torque (per unit) to rated torque (per unit), representing the motor's ability to handle loads beyond its rating. A higher ratio indicates better overload capability and motor performance.

Causes of overload include: 1. Mechanical faults in driven equipment: When the driven machinery has faults, rotates inflexibly, or becomes jammed, it causes motor overload and winding overheating. Load factors must be considered when troubleshooting overheating motors. 2. Abnormal mechanical load operation: Even with properly matched equipment, abnormal load operation with fluctuating demands (e.g., excessive feed rate in threshers) causes motor overload. 3. Improper equipment matching: When motor load power exceeds rated power (

"small horse pulling large cart"), prolonged overload operation causes overheating. Maintenance should first verify load-power matching before disassembly.

Simulation results for a 1300 N · m load are shown in Figures 9 [Figure 9: see original paper] and 10 [Figure 10: see original paper], presenting three-phase current waveforms and electromagnetic torque during overload. Results indicate motor speed reduction (potentially to zero), increased current and heat generation, low humming noise, moderate vibration, and speed fluctuations under severe load variations. Long-term overload operation is extremely detrimental.

Motors commonly experiencing overload include shearers and roadheaders. Prevention measures include using motors with high maximum torque or dual-speed motors that switch to low-speed operation under high resistance.

4.3 Three-Phase Unbalance Operation Analysis

Three-phase unbalance is a common abnormal operating condition. Primary causes include inter-turn shorts in individual windings, faulty starting equipment causing voltage unbalance at motor terminals, resonance, and single-phase grounding. For rewound motors, errors in coil connections or incorrect turns may also cause unbalance [5].

Figure 11 [Figure 11: see original paper] shows electromagnetic torque waveforms when one phase voltage decreases, with 0.5-second simulation time. Severe voltage unbalance increases rotor and stator winding currents, reduces electromagnetic torque, and increases electromagnetic noise.

Under asymmetric faults, Phase A current decreases significantly while stator winding current exceeds rated values. Prolonged unbalance operation can damage insulation in the highest-voltage phase, causing more severe faults such as inter-turn shorts.

5 Conclusion

Analysis demonstrates that the special working environment of coal mines leads to unique fault characteristics in mine three-phase asynchronous motors. Short-circuit, overload, and three-phase unbalance faults frequently occur under harsh conditions. To reduce motor failure rates, comprehensive motor protection devices specifically designed for mine applications should be employed. Additionally, electromechanical equipment management must be strengthened through improved maintenance systems, strict shift handover procedures, enhanced inspection and repair, and complete installation and commissioning records. These measures enable effective operation monitoring and condition diagnosis to ensure motors remain in good working condition.

Note: Figure translations are in progress. See original paper for figures.