Energy balance of asynchronous machine during start-up

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Abstract
The paper deals with energy balance during start-up of induction motor with double squirrel cage. First part concerns with RMS and power analysis of instantaneous values. Second part describes how to obtain particular energy. Thereafter the induction motor was modeled in Matlab-Simulink by equation of state. For mathematical modeling are needed characteristic electrical and mechanical parameters. These parameters were obtained by measuring of the motor in basic modes like no-load and short-circuit test. After that is presented a verification of physically measured and simulated data with subsequent comparison of waveforms. Finally are specified results of energy balance.

1. Introduction
I focused on behavior of the induction motor SIEMENS type 1LA7. Label values are \( U_N=400\,\text{V} \), \( I_N=21.5\,\text{A} \), \( P_N=11\,\text{kW} \) and \( n=1460\,\text{RPM} \). This powered motor was linked by flexible clutch to second motor with similar performance. Stator winding was connected into star and powered by transformer with reduced voltage. Instantaneous phase voltages and currents were recorded by 8-channel digital measuring card, which was connected to PC. Repetition of experiments was tested influence of the parameters on final energy distribution. These thinking parameters were winding temperature, moment of inertia and RMS voltage. Then the motor was modelled by using equations of state. In conclusion is described a verification of physical measured and simulated data.

2. Analysis of measured data
Measured instantaneous values \( u(t) \) and \( i(t) \) were analyzed by equation for RMS value. Real power \( P \) is defined like mean value of product of instantaneous voltage and current.

\[
I_{EF} = \frac{1}{T} \int_0^T i^2(t) \cdot dt
\]

\[
U_{EF} = \frac{1}{T} \int_0^T u^2(t) \cdot dt
\]

\[
P = \frac{1}{T} \int_0^T u(t) \cdot i(t) \cdot dt
\]

3. Energy balance
Particular energies are obtained like area below active power or losses, where limits of integration are from zero to time of start-up. The Fig 2 shows energy distribution in the induction motor.

3.1 Delivered energy from electric grid
It is delivered energy from electric grid to start motor. It depends on area under real power, where limits of integration are from zero to time start-up.

\[
E_P = \int_0^{t_f} P(t) \cdot dt
\]

3.2 Lost energy in supply cable
There was considered lost energy in supply cable, because motors with squirrel cage have high starting currents. Wire resistance \( R_v \) was determined from its geometric dimensions and resistivity.

\[
\Delta E_y = R_v \cdot \int_0^{t_f} I_{EF}^2 \cdot dt = \int_0^{t_f} \Delta P_y (t) \cdot dt
\]
3.3 Lost energy in stator winding

When current passes through stator windings occurs due to active resistance to conversion part of supplied energy into heat energy. Stator winding resistance \( R_1 \) was measured by ohm's method.

\[
\Delta E_{J1} = R_1 \cdot \int_0^t I_{EF}^2(t) \, dt = \int_0^t \Delta P_J(t) \, dt
\]  
(6)

3.4 Lost energy in rotor and mechanical energy

These energies have same size, which corresponds to kinetic energy of a rotating mass at no-load nominal speed. Energy lost in rotor is radiated as heat, while mechanical energy represents useful energy. Both are time independent, but it depends on the moment of inertia and square of angular velocity.

\[
\Delta E_{J2} = E_K = \frac{1}{2} \cdot J \cdot \omega^2
\]  
(7)

3.5 Lost energy in iron and in bearing

This energy is determined by deducting all lost energies and useful mechanical energy from delivered energy. This lost energy is composed of dominant lost energy friction in bearings and lost energy in magnetic circuit.

\[
\Delta E_{Z} = E_p - E_K - \sum \Delta E = \Delta E_{FE} + \Delta E_B
\]  
(8)

determined by measuring of the tested motor in basic modes. Moment of inertia was determined by run out test.

\[
\frac{di_{e\alpha}}{dt} = \frac{1}{L_1} \left( u_{e\alpha} - R_1 \cdot i_{e\alpha} - L_2 \cdot \frac{di_{e\beta}}{dt} \right)
\]  
(9)

\[
\frac{di_{e\beta}}{dt} = \frac{1}{L_1} \left( u_{e\beta} - R_1 \cdot i_{e\beta} - L_2 \cdot \frac{di_{e\alpha}}{dt} \right)
\]  
(10)

\[
\frac{di_{e\alpha}}{dt} = -\frac{1}{L_2} \left( R_1 \cdot i_{e\alpha} + L_2 \cdot \frac{di_{e\beta}}{dt} \right) + \omega \left( L_2 \cdot i_{e\beta} + L_1 \cdot i_{e\alpha} \right)
\]  
(11)

\[
\frac{di_{e\beta}}{dt} = -\frac{1}{L_2} \left( R_1 \cdot i_{e\beta} + L_2 \cdot \frac{di_{e\alpha}}{dt} \right) - \omega \left( L_2 \cdot i_{e\alpha} + L_1 \cdot i_{e\beta} \right)
\]  
(12)

\[
\frac{d\omega}{dt} = \frac{p \cdot M}{J} = \frac{3}{2} \cdot \frac{p^2}{J} \cdot L_1 \left( i_{e\beta} \cdot i_{e\alpha} - i_{e\alpha} \cdot i_{e\beta} \right)
\]  
(13)

5. Conclusion

Measured and simulated waveforms are similar, but exists some differences between them. Generally model rarely can describe behavior of motor quite accurately and precisely because of simplifying assumptions. These assumptions are same size of resistances and inductances in all phases, neglected losses in magnetic circuit and mechanical losses, squirrel cage rotor and expected linearized magnetization characteristic.

Fig 4. Display start-up characteristics with parameters:
\( J=0,23 \text{kgm}^2, T_1=23^\circ \text{C} \) and \( U_{E5}=68V \)

Bibliography


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