Synchronous reluctance motor for electric mine locomotive

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Abstract. The paper presents the way of improving reliability of an electric traction drive of mine locomotives. Practicability of replacement of a DC machine by a synchronous reluctance motor is studied. Advantages of this type of this motor are introduced. Also, the theory of operating is considered. The motor’s topology is described. Operating performance curves of the designed motor are presented.

1. Introduction
Special electric mine locomotives are used for delivery of extracted commercial minerals nowadays. Locomotives that use DC machines as the traction motor are trains fleet mainstay. This is about 75% of the total number of locomotives [1]. However, a DC machine has some disadvantages: necessity of timely maintenance service of the commutator-and-brush assembly, its limited service life, sparking of the commutator that involves a risk of fire and explosion. Using of this machine reduces reliability of the traction drive and need for additional input requirements.

The goal of the current work is improving reliability of the electric traction drive of mine locomotives. To achieve this goal, it is necessary to replace DC machine with power ratings of 7.5 kW.

The paper presents study on replacement of the DC machine by the synchronous reluctance motor (SynRM). The SynRM shows great potential. It should be noted that lack of rotor winding and permanent magnets is the main advantage of SynRM. There are no rotor copper losses. Also, it leads to the reduction of manufacturing costs. Other advantages of SynRM are low inertia, simple construction and operation [2].

2. Theory of operating
The SynRM operation relies on the reluctance torque, which depends on the saliency, defined as the ratio between the inductance in the direct and quadrature axes.

The SynRM operating principle can be explained by a simple example. There are two objects that are presented in figure 1. The first has anisotropic geometry and the second has isotropic geometry. The first object has two axes: direct with maximum magnetic conductance and quadrature with minimum magnetic conductance. The second object has equal magnetic conductance along any axis. Let us apply external magnetic field. The first object tries to reduce magnetic resistance of magnetic circuit. That is why a force that rotates this object appears. However, the second object stays motionless.
Figure 1. The SynRM operating principle.

Reluctance torque produced by the SynRM is equal to that of the conventional synchronous machine with no field current. Rotating magnetic field appears when the stator winding is supplied by AC. The rotor rotates by setting its direct axis along sense of magnetic field.

There is a vector diagram of SynRM, operating at a constant frequency of supply voltage [3].

Figure 2. Vector diagram of SynRM, operating at constant frequency of supply voltage.

According the vector diagram, the following equation can be obtained [4]:

$$\dot{U} = j\dot{i}_q x_{ad} + j\dot{i}_d x_{aq} + j\dot{l}_d x_l + \dot{i}_r r.$$ 

This equation can be represented as:

$$\begin{cases}
U \cos \theta = I_d \cdot 2\pi f L_d + I_q r \\
U \sin \theta = I_q \cdot 2\pi f L_q - I_d r \\
\end{cases}$$

Angle $\theta$ is usually taken as an independent variable in SynRM operating theory [5]. It is shown in figure 2. This angle determines the loading rate. The equivalent circuit of SynRM can be obtained in this basis [4]. It is presented in figure 3.
Operating performance curves can be calculated with the aid of the equivalent circuit of SynRM and the value of $x_d$ and $x_q$.

3. Stator
One of the major advantages of the SynRM is the fact that stator structure is identical to the one used in conventional 3-phase Induction or Synchronous Machines. That is why, the stator of SynRM is the same as a stator of 4A series induction motors (IM) in this study. The manufacturing process of producing this type of machines is mature. So it allows one to lower the total cost of machine.

The goal of the work is to replace the DC machine in the operating electric traction drive. That is why, the machine must have smaller or similar dimensions. Dimensions of the chosen induction motor’s stator are smaller than dimensions of the replaceable DC machine. Power rating of the chosen induction motor is 11 kW.

The number of pole is 4. The number of slots is 36. Winding topology is one-layer concentric [6]. The winding diagram is presented in figure 4.

4. Rotor
There are several rotor structures of SynRM: a flux-barrier rotor, a segmented rotor (Transversally Laminated Anisotropy - TLA) and Axially Laminated (ALA). These structures are presented in figure 5. TLA structure has a simple construction. So, manufacturing costs are lower. That is why the TLA rotor structure is to be used in SynRM in the current paper.
The saliency ratio in SynRM must be as high as possible. So the machine produces the maximum torque. Flux in $d$ axis should be as high as possible while flux in $q$ axis should be minimized. To minimize the flux in $q$ axis, the flux barriers should be as wide as possible, but at the same time the amount of iron in $d$ axis is reduced which causes $d$ axis flux to decrease [7]. That is why it is important to find the right thickness of flux barriers which gives the maximized saliency ratio.

Many rotor topologies are considered as computer electromagnetic simulations. Width and the number of flux barriers are the variable parameters. Maximum torque and low torque ripple are the selection criterions. Few appropriate rotor topologies are selected. Then, they are compared and the best one is chosen. The chosen rotor topology is presented in figure 6. Electromagnetic simulations are performed in FEMM software.

5. Results
As previously noted value of inductance $x_d$ and $x_q$ are necessary to calculate operating performance curves. Electromagnetic simulations are performed to obtain $x_d$ and $x_q$. Firstly, rotor's direct axis is located along magnetic field that is created by stator winding. In this position the value of inductance $x_d$ is obtained. Then rotor's quadrature axis is located along magnetic field and the value of inductance $x_q$ is obtained. Flux lines in the machine on the first and the second rotor positions are presented in figure 7.

Figure 5. Rotor structures: a – axially laminated anisotropy; b – transversally laminated anisotropy.

Figure 6. Chosen rotor topology.
After that, operating performance curves of the designed machine are calculated. The value of parameters is obtained for load angle $\theta$ from 0 to 40 degrees with 0.5 degree step. Table 1 presents the value of parameters for 10, 20, 30, 40 degrees. Operating performance curves are presented in figure 8.

Table 1. Value of parameters for variable load angle $\theta$.

| $\theta$ (deg) | 10  | 20  | 30  | 40  |
|----------------|-----|-----|-----|-----|
| $P_1$ (kW)    | 6   | 10  | 13  | 15  |
| $P_2$ (kW)    | 5.1 | 8.7 | 11  | 12  |
| I (A)         | 22.5| 28.5| 35.4| 42.3|
| M (N·m)       | 33.2| 56.5| 72  | 77.8|
| $\eta$        | 0.85| 0.87| 0.85| 0.82|
| $\cos\phi$   | 0.4 | 0.53| 0.56| 0.52|

Figure 7. Flux lines in machine: a – rotor direct axis is along magnetic field; b – rotor quadrature axis is along magnetic field

Figure 8. Operating performance curves.
It seems essential to emphasize that there is no additional heat in the rotor due to the lack of the rotor winding. That is why the temperature of SynRM is lower than IM that provided a basis for it. This allows to increase electric power and torque of SynRM by increasing electric loading without rising the total losses level [5]. So, the designed SynRM has 9.9 kW power rate with the same losses level as IM. Further increasing of electric loading will require detailed heat calculation.

6. Conclusions

The SynRM as a replacement of the DC machine in the electric traction drive of the mine locomotive is designed. SynRM consists of the stator of the conventional IM and TLA rotor. The designed machine has required dimensions. Operating performance curves of the machine is calculated. These curves show that SynRM has necessary power of 7.5 kW. Also, this machine has 9.9 kW power rate with the same losses level as IM that provided a basis for the designed machine.

References

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