This work shows the results of the tests on a 600/1050kW two-speed synchronous motor with the nominal speeds of 500 and 600 rpm. Motors of this type with powers ranging from 600 to 3150kW are modified single-speed motors. They have been working for several years in coal and copper mines. The use of two-speed drive motors makes it possible to regulate the speed in steps and, thus, regulate the output of the fan and the power drawn by the motor. The possibility of reactive power compensation is intact and mitigation of the motor starting processes is achieved.

1. INTRODUCTION

Two-speed synchronous motors were built by replacing the stator winding with a switchable winding and connecting the rotor winding with two pairs of slip-rings located on the opposite sides of the machine. By switching the windings, two different but close in value, numbers of pairs of poles are obtained. Thus, two rotating speeds, differing in values by anywhere from 10 to 20 percent are obtained. Motors of this type, 600 to 3150kW, have been successfully employed for several years in coal and copper mines to drive main fans of the mine exhaust system [1], [2], [3]. The use of two-speed drive motors makes it possible to obtain the required regulation of the speed and, thus, the required change of the output of the fan. The basic advantage of adapting the output of the fan to actual needs is the lowering of the power drawn by it. Speed change from 600 to 500rpm lowers the output of the fan by 17% and the power it draws by 42% [4], [5]. Two-step start of the two-speed motor shows longer starting time but lower maximum starting current than that of a single speed motor and significantly lower reduction of the voltage during startup. A two-speed motor usually works with higher speed. At that speed, the normal ability to compensate reactive power is preserved. Periods of lower demand for air are work free days, equipment repair and maintenance periods, inspection...
times etc. In those periods, the demand for capacitive reactive power is very low therefore, with the lower speed working conditions, the need for reactive power compensation is not anticipated. Asymmetric winding of the stator and asymmetric connection of the field winding while working at the lower speed, result in deformation of the stator currents, non-uniform warming of the machine elements and increased level of motor frame vibration. Establishing the permissible level of these negative occurrences is the scope of the tests described in this work. The tests on the motor were conducted during the manufacturing phase and also after the motor was installed in work position in the mine.

![Tested synchronous motor coupled with fan](image)

During the tests the following values were monitored: voltage, armature and field currents as well as the rotating speed during direct starting, asynchronous running at the set value, synchronization and loading of the motor on both rotating speeds. Vibration of the bearings and motor frame as well as the temperature distribution were also monitored. Recording of the armature currents of the loaded motor and analysis of its harmonics made it possible to assess the degree of the current distortion caused by the asymmetry of the magnetic circuit. That asymmetry was the condition for obtaining the second, lower rotating speed. Asynchronous running allowed determination of the synchronous reactance of the machine in both of its axes. This work shows the results of the tests on a 600/1050kW motor (fig. 1 and 2).

This motor is unique in that its field winding may be connected using 8 or 10 poles. Theoretical considerations and the results of calculations lead to the conclusion that the complete disconnection of two poles, may affect positively the functioning of the machine at the lower speed and negatively at the higher. Establishing the degree of this influence and, thus, the usefulness of disconnecting of the two poles, were the additional scopes of the conducted tests.
2. TWO-STEP STARTUP

Before coupling the motor with the fan, startups of the motor in both winding connection configurations were tested. The results of the direct asynchronous startup to 500 rpm are shown in figure 3 and to 600 rpm in figure 4. Startup to the higher speed occurs faster but the amplitudes of the armature current reach values of over 1000A. After coupling the motor with the fan, the startup process takes so long that the direct startup to 600 rpm is impossible. Prolonged overload triggers the reaction of the supply system protection. Figure 5 shows two-step startup, without synchronization. Startup time of the motor coupled with the fan lengthen from 3.5 sec to 30 sec. After reaching the lower asynchronous speed the stator and the rotor windings were switched and after 2.5 sec the motor reached the second, larger asynchronous value. On the second startup step, at the first moment of the startup, the armature current amplitudes reached a value close to 1000A but decreased almost immediately. After stabilization of the speed, the values for the armature currents are 1.6 times higher than nominal currents and their cyclical values fluctuate from 190 to 225 A. This is caused by the reluctance moment. After connecting the field current, the armature current diminishes to half of the nominal value (figure 6). The two-step startup and synchronization shown in figure 6 differ from the normal startup procedure. Synchronization for both synchronous speeds was conducted in one trial. In a normal startup procedure to the higher speed, synchronization for the lower speed is not conducted. Startup trials for the motor coupled with the fan were carried out in the same fashion for 8 and 10 poles connected. Obtained current and voltage functions are almost identical.
Fig. 3. Startup without a fan up to 500 rpm

Fig. 4. Startup without a fan up to 600 rpm

Fig. 5. Two-step startup without synchronization
Fig. 6. Two-step startup with synchronization at each step

3. COMPENSATION RANGE

While modernizing the motor the assumption was that it would maintain the compensation range for the higher speed. For the lower speed, the lagging power factor would be no less than 0.8. The scope of the compensation trials was to verify which variant (8 or 10 active poles) would better accomplish these conditions. In all the trials, the field current of the loaded machine was changed from the maximum value (established in heating trials) to that at which the machine would fall out of synchronism. The results are compiled in figures 7 and 8.

Fig. 7. Reactive power compensation for two variants of the motor working at 600 rpm
In order to establish maximum obtainable values of the power factor for both synchronous speeds, the harmonic analysis of the currents and voltages corresponding to the maximal field current, was conducted. This way the functions of the phase current and voltage basic harmonics were obtained. The phase shift of those allowed to determine the power factor value.

Maximum values of the power factor obtained from the analysis of the recorded functions are compiled in table 1. Both, curves V as well as the established maximal values of the power factor, indicate that the motor with 8 active poles will not allow it to obtain a leading power factor.

### Table 1. Maximal values of power factor.

<table>
<thead>
<tr>
<th>n [rpm]</th>
<th>Poles number</th>
<th>Power factor</th>
<th>I_f [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>10</td>
<td>0.819</td>
<td>leading</td>
</tr>
<tr>
<td>600</td>
<td>8</td>
<td>0.966</td>
<td>lagging</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>0.866</td>
<td>lagging</td>
</tr>
<tr>
<td>500</td>
<td>8</td>
<td>0.809</td>
<td>lagging</td>
</tr>
</tbody>
</table>

## 4. CURRENT DISTORTION

In all the considered cases significant distortion of the stator current takes place after synchronizing and loading of the motor (fig. 9, 10, 11 and 12). Furthermore, working with lower rotating speed causes some distortion of the voltage (fig.13 and 14)
Fig. 9. Motor current functions at 500 rpm

Fig. 10. Motor current harmonics at 500 rpm

Fig. 11. Motor current functions at 600 rpm
The least distorted, for obvious reasons, is the current of the motor with 10 poles working at 600rpm. Current distortion at lower speed is slightly lower for the 8-pole motor. However, this solution is definitely worse for the higher speed (fig. 12).

Fig. 12. Motor current harmonics at 600 rpm

Fig. 13. Motor phase voltage functions 500 rpm
5. VIBRATION TESTS

Intentional introduction of field current asymmetry which is the condition to obtain the second, lower rotating speed, may cause an increase in vibration levels. Results of the tests conducted on bearings and the stator of the loaded machine are shown in figures 15, 16 and 17. Velocity spectra of the bearing vibration are similar for both synchronous speeds, although, the dominant velocity harmonic is the first harmonic for the higher speed and the eighth harmonic for the lower. In the latter case the first harmonic is lower than for the higher speed. For the higher speed, other than the first harmonic also the twentieth harmonic reaches a significant value. No significant impact of the magnetic asymmetry on bearing vibration could be observed; furthermore the level of vibrations does not exceed allowable values. Vibrations manifest differently on the frame of the stator. The symmetric machine working at 600 rpm does not experience large stator vibrations. The largest are harmonics 10 and 20 and their velocity values are similar to those for the bearings. However, the rotor of the motor at 500 rpm vibrates much stronger. Its vibrations intensify with the increase of the field current, thus pointing out to the source of these vibrations. At this rotating speed, the second harmonic (in radial direction) and the eighth harmonic (in all directions) reach large values. Also, the tenth harmonic of significant value is active in the axial direction. Rotor vibrations at lower speed are five times as large as those of the bearings. Although norms do not establish allowable stator vibrations, their value was considered the limiting factor for the rise of the field current. This limitation results in the attained power factor for lower speed. Power factor for that speed and field current of 230A reaches the value of 0.87 lagging, when for the higher speed and field current of 260A the achieved value is 0.82 leading.
Fig. 15. Vibration velocity spectra of the bearing L1 of the tested motor

Fig. 16. Vibration velocity spectra of the bearing L2 of the tested motor

Fig. 17. Vibration velocity spectra of the stator of the tested motor
6. HEATING

Thermographic temperature measurements for the tested machine were conducted using an infrared camera and a pyrometer. The scope of these measurements was to detect the most heated elements of the motor and unevenness of the heating.

Fig. 18. Thermogram of the warmed-up motor longitudinal elements like pipes used as transportation

Fig. 19. Thermogram of the screws tightening the stator core
The field winding temperature reached 50°C (fig. 18) and was higher than the temperature of the front part of the stator winding. The most heated elements turned out to be the long tightening screws of the stator core (fig. 19). On the perimeter of the machine there are 12 of these screws, evenly distributed. Two pairs of neighbouring screws (fig. 19) have a temperature significantly higher than the remaining. The screws reach especially high temperature when the motor works at the lower speed and at the high field current value. Somewhat lower temperatures are reached by other longitudinal elements like pipes used as transportation handles or frame ribs (fig. 20).

7. CONCLUSIONS

The results of the tests prove that the two-speed synchronous motor accomplishes what was expected of it, namely, it assures step-regulation of fan efficiency in assigned proportions and mitigates the motor starting process. The mitigation of the motor starting process lies in the fact that the high startup currents appear for a very short time after the switch over of the windings takes place. The negative effects while the motor is working at the lower speed that is the elevated vibration of the stator and the elevated temperature of some frame elements are function of the field current value. Limiting this current brings both, the vibrations and the temperatures to the acceptable values but limits the reactive power compensation at the lower rotating speed.
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REFERENCES


