Vibration Based Broken Bar Detection in Induction Machine for Low Load Conditions

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***Abstract*—A new method for broken bar detection, based on vibration signal analysis, is presented in this paper. While there are several methods for broken bar detection at low slip based on the current signal analysis, detection based on vibration signals attracts much less attention. In the current paper, detection of the broken bar was conducted by observing fault frequency content of the modulus of the analytical vibration signal. A broken bar feature is extracted from low frequency range even for low slip conditions. Although this method is successfully used for broken bar detection based on current signal analysis, it is important to verify the method when vibration signal is measured. Procedure is verified in a real industrial environment for induction motor of 3.15 MW.**

***Index Terms*—motor, bar, vibration, fault, detection.**

I. Introduction

Because of their robust configuration, low cost per unit and relatively small size, induction motors (IMs) are a working horse of the industry. They have found irreplaceable role in many industrial and domestic applications where electro-mechanical conversion is required. During their lifetime, IMs are exposed to mechanical, thermal and electrical stresses, which can cause failures in different motor parts. These failures can harm a process or environment. The high power IMs (MW power range) are especially critical when a failure occurs. Often they are crucial parts of an industrial process and malfunction can cause production to stop. High power IMs are expensive, and cost of repair and transportation is high [1].

Robustness and reliability are of high interest, especially for high performance applications [2]. Fault detection of induction machines has received a significant attention in academic and industrial societies [3]. Early fault detection and condition monitoring has several advantages in comparison with periodical maintenance procedures. Reliability of the system is increased with minimal financial investment. List of spare parts can be significantly reduced. Moreover, the machine life can be prolonged and the performance and the availability of machine can be increased.

IMs suffer from several type of faults including stator, rotor and bearing faults, as shown in Fig. 1.

The fault detection of IMs is based on the following procedure. Physical signals are measured and acquired by sensors and supporting instrumentation. The signals are then analyzed by different techniques, extracting the fault features which can indicate presents of the fault [3, 4].

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Over the years, many condition monitoring methods have been proposed [5]. They monitor some parameters of the motor, thereby determining its condition. Various IMs variables are measured, such as: acoustic noise, electromagnetic field, air-gap torque, voltage, instantaneous power, vibration, stator current and others [1-5].

In this paper, a steady state vibration signal is examined to determine presence of broken bar fault in a real industrial environment. The application of interest is a thermal power plant drive for high and low pressure pumps. The pumps are driven by 3.15 MW induction motors with one of them showing signs of mechanical fault. Since low load conditions implicate difficulties in extraction of usually observed broken bar features, a new features are proposed, based on frequency content of the modulus of the analytical vibration signal. These features are widely used in fault detection based on current signal analysis, but, by the author's best knowledge, they are used for the first time in this research for a broken bar detection based on vibration signal analysis for the high power IM.

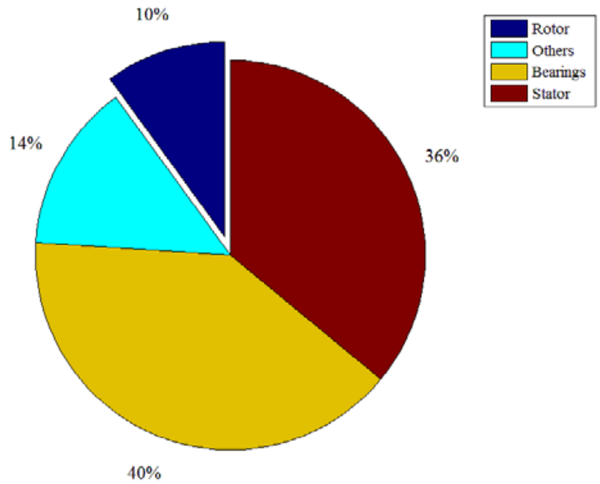

Figure 1. Typical faults of induction motor

II. Detection Of Broken Rotor Bar Using Vibration Analysis

Rotor faults take around 10% of all IMs faults, as shown in Fig. 1. Rotor bars can be damaged during the IMs operation. Broken bar fault is caused by mechanical stresses, imperfection in material or the rotor construction. Once the rotor bar cracks, the neighboring bars condition also deteriorates. The increased bars stress causes the fault progress and the increase of the number of broken bars, which can cause rotor to collapse. To avoid such situation, the fault should be isolated as early as possible [1, 4].

Various signal processing techniques are used to obtain reliable broken bar features at early failure stage. The great number of methods is based on phase current or vibration signal analysis to determine presence of broken bar. Steady state and transient regime are examined. Motor current signature analysis (MCSA), which considers steady state conditions [6], represents a fundamental approach to broken bar detection. Motor vibration signature analysis (MVSA) is used on the vibration steady state signal [4]. Techniques based on inspection of an amplitude spectrum obtained by fast Fourier transform (FFT) have several disadvantages when low load conditions are applied. Method based on the inspection of low frequency domain of the modulus of an analytical current signal in a steady state shows reliable broken bar detection even at very low load [7]. To make detection process autonomous, support vector machines (SVM) classifier can be used to distinct healthy motors from those with broken bars [8, 9]. Fault detection can be supported by fuzzy logic [10] or artificial neural networks [11]. Finite element method (FEM) can be used to obtain valid fault model [12]. To avoid difficulties in steady state for low load conditions, transient analysis is discussed. Advanced techniques like Digital, Continuous or Harmonic Wavelet Transforms can be applied to obtain reliable broken bar feature during a startup [13-19]. Practical implementation of diagnostic system is achieved by use of a digital signal processor (DSP) [20].

For detection of mechanical failures like gear root crack, gear mesh defects, bearing problems, helical gearbox faults, rotor misalignment and mass unbalance, it is common to use vibration signal analysis [21,22]. However, this fault detection technique can also be used to detect broken rotor bar. This fault is manifested by exciting the electromagnetic field disturbance and by the increase of the torque modulations and vibrations of the motor. These irregularities can be detected using vibration sensors mounted on a motor housing [23].

Frequency content of the measured vibration signal shows fault specific features. Feature position in amplitude spectrum implies presence of particular fault. Extracting the discriminative features is the key issue for successful broken bar detection [4].

Classic approach in vibration-based broken bar diagnosis relies on detection of increased amplitudes in vibration signal spectrum, at rotation frequency sidebands. Such an approach is explained in detail in [23] and it is common in literature and widely used in practical applications. However, these characteristic fault features are highly slip-dependent. If the slip value s is low, the rotation frequency f_r is near to synchronous speed f_s, so the sidebands will be hidden and less distinctive in signal spectrum. Therefore, if the load and the slip value are low, the fault detection reliability is questionable, when this classical fault detection technique is used.

To avoid these issues, the vibrations need to be measured in operation point close to rated load, in order to clearly distinguish sidebands from the central frequency. This is the main drawback when using rotation speed sidebands as features for fault detection, meaning that low load level and low slip are undesirable.

Same problems also occur when current-based detection of broken rotor bar is used, since at low slip conditions, characteristic sidebands are also close to central frequencies and it is very difficult to identify their presence. To overcome these difficulties, a novel method is proposed [7]. It relies on the analysis of the amplitude spectra of the modulus of the analytical signal. This approach is successfully used for broken bar detection based on current signal analysis, especially for low slip conditions at steady state. However, by the authors' best knowledge, this method was not yet considered for vibration signal analysis at MW range motors.

Mechanical vibration and stator current are mutually dependent, since the rotation of the rotor is a consequence of electromagnetic field induced by stator current. Therefore, all characteristic changes present in the current signal can also be noticed in motor vibration signal, which is a mechanical indicator of motor state. Guided by this analogy, the authors propose the application of method described in [7] for detection of broken rotor bar based on vibration signal analysis, which will be explained in the sequel.

If there is no broken bar (or other faults), a dominant component in motor vibration signal has pure periodical nature:

$$x_h(t) = X_m \cos(\omega t), \tag{1}$$

where ω is the rotation speed. When broken bar occurs, the vibration signal is modulated with fault frequency

$$x_b(t) = x_h(t)\left[1 + \frac{n_b}{N_b}\cos(\omega_0 t)\right], \tag{2}$$

where following notations have been used: ω_0 is fault frequency, n_b is the number of broken bars and N_b is number of rotor bars. Depth of modulation is directly proportional to the number of broken bars.

To obtain the analytical vibration signal, Hilbert transform is used:

$$HT[x(t)] = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}d\tau. \tag{3}$$

HT of analytical function is the analytical function with phase shift of 90 degrees, so there is no change in frequency content [20]:

$$HT\left[\sin(\omega t)\right] = \cos(\omega t). \tag{4}$$

Analytical vibration signal of healthy machine is given by following expression

$$\vec{x}_h(t) = X_m e^{j\omega t}. \tag{5}$$

If the broken bar fault is present, a pulsation is present in the modulus of the analytic signal, with the characteristic frequency of the machine fault:

$$\vec{x}_b(t) = \left[1 + \frac{n_b}{N_b}\cos(2\pi(2sf_s)t)\right]X_m e^{j\omega t} \tag{6}$$

$$\left|\vec{x}_b(t)\right| = X_m + \frac{n_b}{N_b}\cos(2\pi(2sf_s)t)X_m \tag{7}$$

Observed variable is obtained by removing direct component:

$$X_b(t) = \frac{n_b}{N_b}\cos(2\pi(2sf_s)t)X_m. \tag{8}$$

A single feature related to the broken bar is obtained from variable given in (8). Position of the feature in low frequency range is defined by slip value as rotation frequency is held constant. If the number of poles is 2, the position of the feature will be numerically equal to the slip value given in percentage and will not be covered by dominant frequency.

To obtain the signal spectrum of observed variable (8) the FFT is used. FFT is calculated in the number of points equal to the number of samples in observed signal [7].

III. Experimental Results and Verification

The above described method is tested in the laboratory and in the real industrial environment. The laboratory setup is depicted in Fig. 2. Induction machine has 11 kW, four poles and it is supplied from the mains 3x400 VAC. Two rotors have been used, one is considered healthy and other one has one bar deteriorated by drilling. Radial vibration signal was acquired for 25 seconds, with sampling frequency of 25.6 kHz. The fans were removed to additionally decrease slip. Machine was not loaded during examination, which resulted in very low slip (approximately 0.12%) and rotation speed close to synchronous. Obtained results are depicted in Fig. 3. Two clearly distinguished features are shown at low frequencies, which indicate broken bar fault. These results verify the applied method in laboratory conditions.

Figure 2. Laboratory setup for broken bar detection based on vibration signals

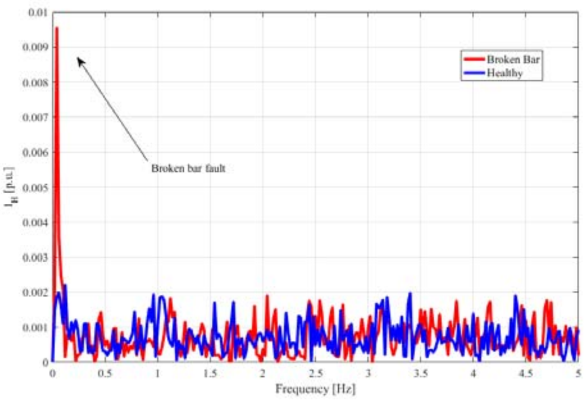

Figure 3. Broken bar fault detection in the laboratory conditions

To further verify the applicability of the proposed method, fault detection was conducted for 3.15 MW high-voltage induction motor in thermal power plant application, which was used also as a research object in [23]. The same research object is used to compare the efficiency of classic fault detection technique and newly proposed method. , i.e. the research object is considered as a benchmark facility.

The rotor of the tested motor has 56 bars. It drives a low- and a high-pressure pump in a heating plant depicted in Fig. 4. There are two identical process lines. This application presents a real industrial environment and a good test ground for examining applicability of the presented methods for broken bar detection.

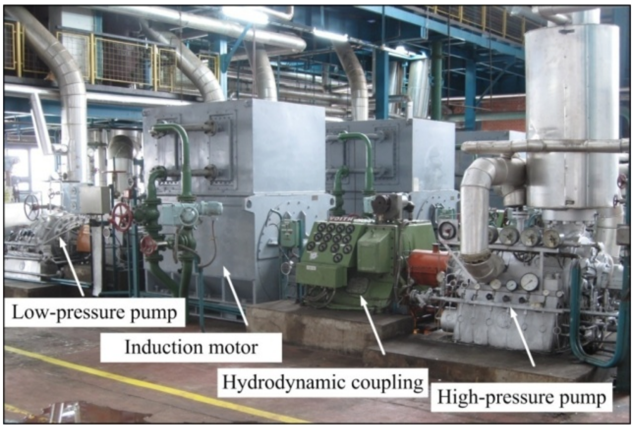

Figure 4. The 3.15 MW induction motor in the heating plant

This motor operated with high level of vibration and acoustic noise. The momentum was decreased under high load, which are all symptoms of the broken bar fault. However, the disassembling and rotor removal were considerably expensive and it was crucial to detect, isolate and eliminate the fault.

Vibrations were measured by accelerometers of 100 mV/g sensitivity, mounted to the housing by magnetic mounts (see Fig. 5). Axial and radial vibration signals were acquired, with 10 kHz sampling rate. For data acquisition NI USB-9234 card was used.

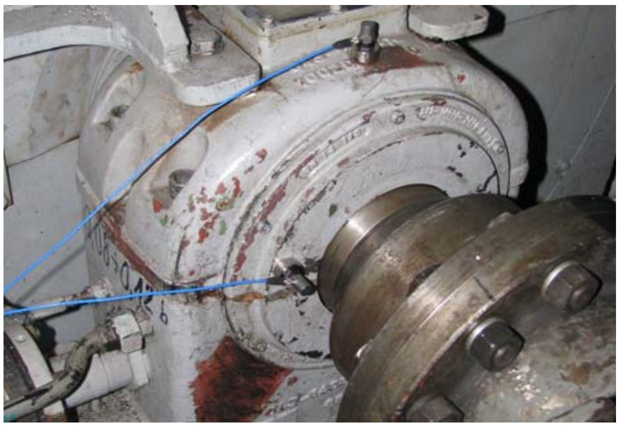

Figure 5. Shear accelerometers with magnetic mounting

The signals were acquired from two identical motors. One of them was the observed faulty motor, and the other one was the healthy motor, taken as a reference [23], with same characteristics, driving the same type of pumps. Fig. 6 and Fig. 7 depict acquired vibration signals in time domain for low load steady state conditions, respectively for healthy and faulty motor, where g is 9.81 m/s^2. Duration of signals acquisition is 10 sec.

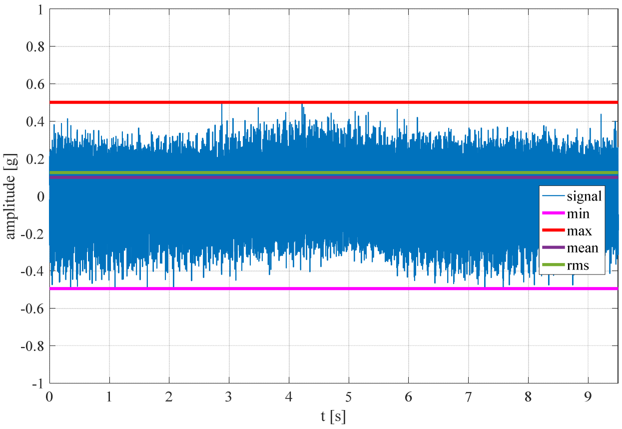

Figure 6. Vibration signal of the healthy motor in time domain

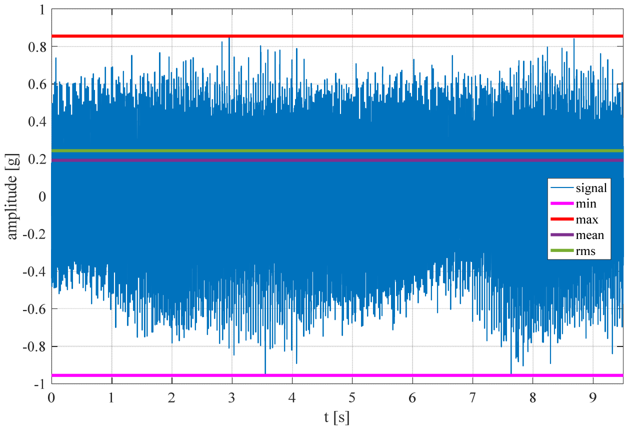

Figure 7. Vibration signal of the faulty motor in time domain

Table I gives some basic statistics for acquired signals: min, max, absolute mean (9), root mean square (10), kurtosis (11) and skewness (12). These statistical parameters can be used to assess the condition of rotating machines [8, 22]. Vibration signal of the faulty motor has higher values for min, max, mean and RMS in comparison with values obtained from vibration signal of the healthy motor, for similar working conditions. This is a clear indication that potentially faulty motor has indeed same sort of a fault. The increase in vibration magnitude is clear indication of rotor fault. Kurtosis is the statistic feature used for detection and isolation of faults [24]. For normal distribution kurtosis has value of 3. Potentially faulty motor has kurtosis slightly under 3; contrary, the healthy motor obtained kurtosis value just over 3. Skewness is the indicator of the data asymmetry around the sample mean. Skewness can take positive and negative values. For healthy motor, skewness is positive and for potentially faulty motor, it is negative.

The following task is to determine which type of rotor fault is present. By observing just a time domain of the vibration signal and his statistic presented in Table I, the type of the fault cannot be reliably determined; only the presence of some fault is indicated. To switch perspective, analysis of vibration signal in frequency domain is necessary.

$$\mu = \frac{1}{N}\sum_{i=1}^{N}|x_i| \quad (9)$$

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}|x_i|^2} \quad (10)$$

$$k = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^4}{\left(\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2\right)^2} \quad (11)$$

$$s = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^3}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}\right)^3} \quad (12)$$

TABLE I. VIBRATION SIGNAL STATISTICS

Statistics	Healthy	Faulty
Min	-0.4947 [m/s^2]	-0.9555 [m/s^2]
Max	0.5014 [m/s^2]	0.8552 [m/s^2]
Absolute mean	0.0999 [m/s^2]	0.1928 [m/s^2]
RMS	0.1256 [m/s^2]	0.2435 [m/s^2]
Kurtosis	3.0674	2.9368
Skewness	0.1533	-0.0080

The plant was not in operation when fault detection and diagnosis were conducted. Vibration signals were acquired at two different operation points, with different load levels, i.e. approximately 27% of nominal load for the first, and 37% for the second operation point. The nominal load could not be achieved. The slip was measured using stroboscope. For the first operation point, slip was measured to be 0.0010 (0.10%), and for the second operation point it was 0.0016 (0.16%). The rotation speed was 49.95 Hz for the first, and 49.9 Hz for the second operation point. There are two pole pairs in the motor, and the mains frequency f is 50 Hz, which is equal to synchronous motor speed f_s.

In [23], classic broken bar detection was conducted and characteristic features were calculated using these data. Because of low load conditions, and consequently low slip, broken bar characteristic features and its magnitude were hard to extract. Due to spectral leakage, fundamental frequency covers characteristic side bands and faulty condition was very hard to detect, especially at the lower load level.

To overcome this drawback, spectrum of the modulus of vibration analytical signal will be observed, instead of spectral analysis of measured vibration signal, as explained in preceding text. Fig. 6 and Fig. 7 show frequency spectrum for healthy and broken bar motors. Amplitude peak on the frequency verifies the existence of broken bar. Considering observed signal (8), characteristic pick, which indicates broken bar presence, will appear at $2sf_s$ frequency. In the case of healthy motor, maximum pick value is below 0.004 p.u. (see Fig. 8). In the case of faulty motor, maximum pick value is over 0.009 p.u., as shown in Fig. 9.

For faulty motor, pick at frequency $2sf_s$ has more than two times greater magnitude then in the case of healthy one. Change in magnitude is significant and thus reliable diagnostic can be made.

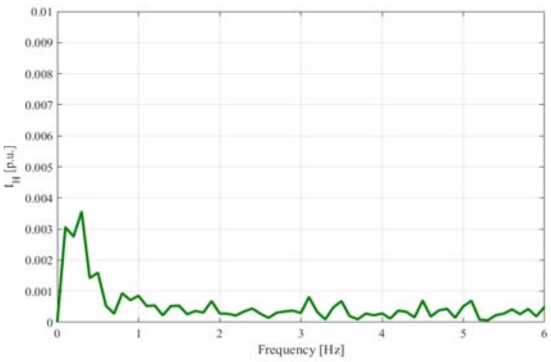

Figure 8. Frequency content of the modulus of analytical vibration signal for healthy motor

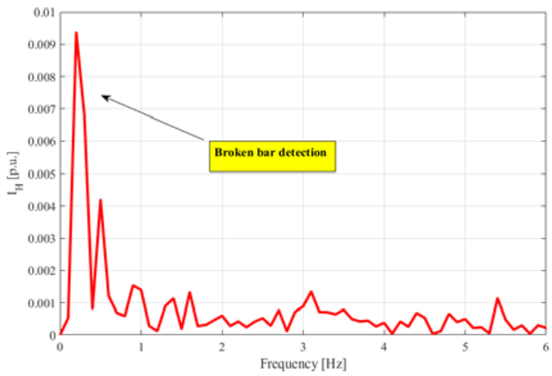

Figure 9. Frequency content of the modulus of analytical vibration signal in broken bar case

To verify the result claimed by inspection of motor using vibration signal, fault detection is conducted applying motor current signal analysis. Obtained spectrums are shown in Fig. 10 for healthy and broken bar motors. Current was measured by digital acquisition card and a measuring transformer 400/5 A, with sampling frequency set to 5 kHz. Induction motors are supplied directly from the mains [25]. Some resent research proposes use of single-phase AC voltage as a test signal on the motor terminals resulting in a stator backward rotating magnetic field which causes additional current components in the stator windings even if the motor is unloaded [26].

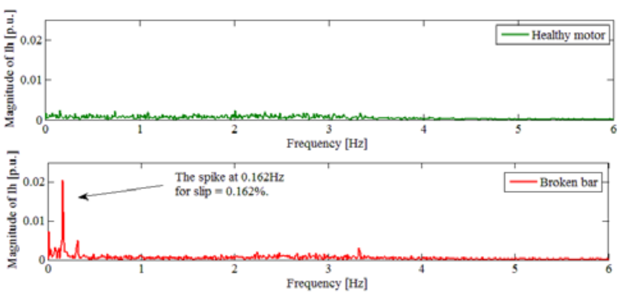

Figure 10. Frequency spectrum of the analytical current signal (slip 0.16%)

Presented results indicate that broken bar fault is present. The tested motor has been disassembled and the visual inspection has verified the presence of broken bar fault. Cracked rotor bars are shown in Fig. 11.

Figure 11. Visual inspection of dismounted rotor confirmed the existence of two cracked rotor bars

IV. Conclusion

An approach for reliable detection of broken bar fault for low load conditions based on vibration signal analysis is shown in this paper. Standard procedures for broken bar detection based on vibration signal analysis are not reliable when the load and slip are low. Broken bar features are covered by rotational frequency and cannot be unambiguously extracted.

Procedure based on frequency content analysis of the modulus of analytical vibration signal overcomes difficulties related to low slip values. This procedure is successfully used for current signal analysis based broken bar detection. Results shown in this paper verified that this procedure can be applied on the motor vibration signals to successfully determine presence of broken bar fault, even for MW range motors.

The procedure is verified in industrial environment for detection of broken bar in 3.15 MW induction motor, which drives high- and low- pressure and operates under very low load and slip conditions. By early detection of broken bar, more severe consequences for the motor and system are prevented. The cost of the diagnostic system is insignificant in comparison with the cost of system failure.

In this research, however, the magnitude of characteristic broken bar features is not discussed, since two identical motors, one of them being healthy and the other being faulty, were examined and the results were compared. Based on this comparison, broken bar was detected beyond any ambiguity. Further research could be devoted to determine the critical value, i.e. the threshold for characteristic features, in order to establish a reliable vibration-based broken bar detection method.

Appendix

Number of poles: 4; Rated power 3.15 MW; Rated voltage: 6 kV; Rated frequency: 50 Hz; Rated current: 373 A; Rated speed: 2982 rpm; Stator-winding connection: star; Rotor type: squirrel-cage, one cage; Number of rotor bars: 56.

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