Detection of Failures on the High-Voltage Cage Induction Motor Rotor

Preliminary Communication

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Abstract *– In recent years, problems of increasing energy efficiency and stability in the work of electric motor drives, are becoming more and more important. Reducing costs of production in many industries should necessarily modernize our technological processes, the introduction of modern electronic devices should raise the level of automation and modern methods of management and protection. Motor efficiency has been significantly increased per volume unit by improving the technology of motor production, which means that less volume per motor power decreases the thermal time constant; therefore, warming-up is faster under abnormal conditions. Advanced HV cage induction motors are constructed for high powers, dimensioned for precisely defined load, also with very low permissible overload. There are many different factors which influence operation of induction motors, and any deviation of some of those factors could cause damage to the motor. This paper will discuss the issues of failures on the high-voltage cage induction motor rotor, the causes of failures and their detection.*

Keywords *– failures, high-voltage cage induction motor, rotor, thermal stress of electric motors.*

1. INTRODUCTION

Improvement in motor manufacturing technology is essential for an increase in motor efficiency per volume unit, which means that less volume per engine power decreases the thermal time constant; therefore, warming-up is faster under abnormal conditions. Advanced HV cage induction motors are constructed for high powers, dimensioned for precisely defined load, also with very low permissible overload. There are many different factors which influence operation of induction motors, and any deviation of some of those factors could cause damage to the motor [1].

Depending on the working mechanisms, working conditions, etc., induction motors can be squirrel cage motors and induction motors with wound rotors or so-called slip ring induction motors. Which of these two types would be used depends on many factors. The most important factors are the mode and the heaviness of a start-up drive, i.e., the operating mechanism. In general, this means that, regardless of whether they start loaded or have great inertia, slip ring induction motors are commonly used in the drives with a difficult start-up. However, this may not be the case. In fact, there are motor drives which have an extremely heavy start-up and those drives are driven by cage induction motors [2].

Despite proper design and dimensioning of power substations, as well as careful installation and maintenance, the facility must reckon with the possibility of failure occurring in almost every part of the power substation, especially on electric drive motors. It is quite clear that it is not rational to construct a motor to endure all possible electrical and mechanical stress which may occur during operation. Due to very high or very low power supply voltage, substantial current overload in the motor can occur. Of course, it should not be forgotten that various transients in the network can cause various dangerous operating conditions of the motor.

As known from theory, conversion of electrical into mechanical energy is done in the rotor. That is why this particular part of the motor is exposed to mechanical and thermal stress. These stresses are not as dangerous in light drives, but in heavy drives they can cause very serious damage to the rotor of the electric motor. This is especially emphasized in cage induction electric motors.

Detection of failures on rotor of the high-voltage cage induction motors is quite complex and requires considerable expertise and theoretical knowledge in this field. Section 2 explains some structural weaknesses of squirrel-cage rotors on high-voltage cage induction motors which influence the occurrence of failures. Section 3 gives an overview of dangerous operating conditions as well as the interaction between the drive motor and the power supply network, which significantly influences the occurrence of motor failure. Section 3 presents a review of high-voltage cage induction motors, especially of breakage on the cage and short-circuit rotor ring of the high-voltage cage induction motor.

2. CONSTRUCTION OF THE ROTOR OF HIGH-VOLTAGE INDUCTION MOTORS

As already mentioned in the introduction, there are two basic types of rotors of induction electric motors. These are:

- cage, and
- slip ring.

In this case, the problem in the rotor of a cage induction motor will be considered. Its positive operating characteristics (a simple structure, high durability and reliability) make it applicable to any facility where technical conditions allow it. A wish to increase the torque during the start-up of the induction motor with the cage rotor led to the emergence of a special rotor, which improves engine performance at the start-up.

Special constructions of cage rotors are (Figure 1 and Figure 2):

- double cage rotors, and
- deep slot rotors.

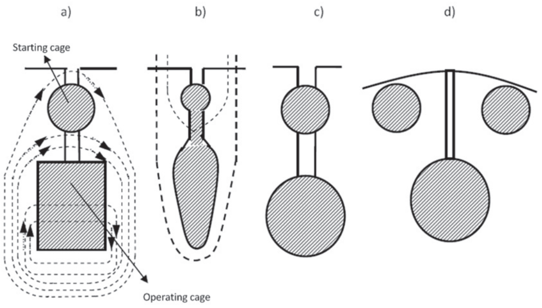

Fig. 1. Different versions of double cage rotors

Practice has shown that the trapezoidal shape of rods is particularly suitable because this kind of cage has very good heat extraction from rods to rotor iron sheet package. This can be explained by the fact that the trapezoidal shape with its large surface lies on the rotor iron sheet package. Precisely for this reason, motors that drive heavy working mechanisms and working mechanisms that have a difficult start-up are made with deep slots or have double cage rotors.

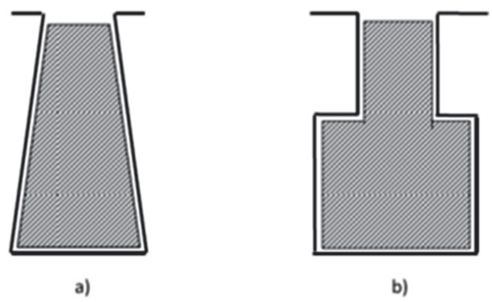

Fig. 2. Trapezoidal and "T" shape deep slot rotor rods

The application of induction motors to heavy drives can be achieved by using the special rotor design with a "free" cage. Figure 3 shows the cross-section of a "free" cage rotor slot.

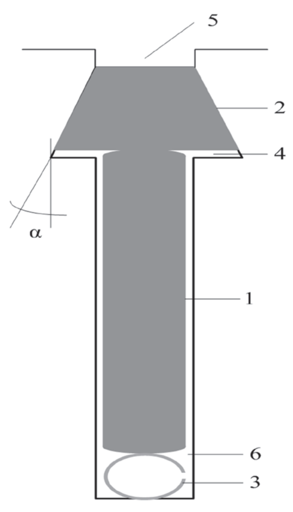

Fig. 3. Cross-section of the "free" cage rotor slot

The lower (operating) cage (1) corresponds to a normal version of the cage. The shape of rotor slots is slightly changed. The lower part of the slot (6) has a rectangular shape and a lower cage rod (1) placed in it, and an elastic feather (3) for driving the upper cage rod (2). The upper part of the slot has a trapezoidal shape and the upper cage rod (2) is placed in it, which also has a trapezoidal shape. Traverse slot and rod sides have the same angle α due to better heat transfer from the rod to the package and minimized cross current transition resistance. The trapezoidal slot part is a few millimeters larger than the trapezoidal rod to make the installation of rods easier. Slot hole (5) is generally equal to the width of the lower rectangular part of slot (6), which enables an easy installation of the lower rod. After installation, rods are tightened with elastic feathers (3) located below lower rods, but they could also be placed between the rods. The upper rods are not connected with short-circuit rings and they represent a "free" cage through which eddy currents and interbar currents flow. Eddy currents flow only in rods, while interbar currents flow close through the rotor iron sheet package [4].

Motor limit temperature classes are defined by thermal insulation as shown in Table1.

Table 1. Motor temperature limit to thermal insulation class

Insulation class	The maximum allowable temperature, ϑ_{max} (°C)
A	105
B	130
F	155
H	180

Normally, all modern motors are built from material of class F, but are designed in a way that the operating temperature does not exceed the limit for class B. This significantly extends the lifespan of motor insulation. If motor protection safeguards the motor with these properties, its task is to prevent the insulation temperature to exceed the value of 130°C at any moment. Clearly, there is a reserve in motor heat capacity. If we disregard this reserve, it is possible to overload the motor, and during continuous operation, insulation temperature does not rise above the maximum temperature for insulation class F. The factor which allows certain motor overload is called an overloading factor and it takes into account standard curves of allowed motor overload as per the IEC 60255-8 standard. This factor allows better utilization of motor heat capacity, but it also significantly reduces the lifespan. For motors for which the manufacturer do not clearly define conditions of working with the overload factor and for all older motors, it is better to take into account the first factor [5].

3. DANGEROUS OPERATING CONDITIONS AND DRIVE FAILURES IN HV CAGE INDUCTION MOTORS

3.1. DANGEROUS OPERATING CONDITIONS IN HV CAGE INDUCTION MOTORS

Electric motor insulation is exposed to various mechanical, thermal, chemical and electrical stress. Insulation breakthroughs have resulted in the occurrence of ground faults and short circuits in motor windings.

Except for failures, motors may be subject to operating conditions that could lead to breakthroughs or burnt-out coils if they are not eliminated on time.

Dangerous operating conditions are as follows:

- motor overload,
- disappearance and return of the voltage,
- inverse phase sequence,
- AC motors working in two phases,
- excessively long run-up,
- unallowed number of consecutive run-ups, and
- blocked (stiff) rotor.

Although the application of a compact system for stator winding insulation achieved great safety at work and almost excluded the possibility of failure in stator windings of cage induction motors up to 6kV, failures still occur. With heavy start-up conditions, cage motor rotor windings are likely to be damaged, because high energy losses in rotor windings are converted to heat, which results in overheating.

Cage rotor damage often occurs in motor drives, especially in large induction motors, although electric motor producers deliver induction motors with high-quality rotors, both in mechanical and electrical aspects. Statistical data suggest that as many as 30% of all failures occur on the rotor of a very large cage induction motor. Therefore, it is necessary to control the quality of the cage rotor and pay great attention to it; otherwise, it may cause very serious damage to the entire motor.

3.2. INTERACTION OF DRIVE MOTORS AND ELECTRICAL NETWORKS

When analyzing the influence of interference from various sources on parameters and operation of electric drives, it is necessary to distinguish between interference occurring in steady state conditions (continuous operation) and interference associated with dynamic states (transient processes).

Interference from the power supply network that may affect the normal operation of induction motors may be as follows [6]:

- non-standard voltage form,
- adjustable voltage magnitude,

- asymmetry of supply voltage,
- frequency change of the power supply network,
- harmonics,
- transient faults in network–AR (automatic reclosing), and
- surges.

When discussing disturbances in the power supply network, which may adversely affect the motor in the electric motor drive (EMD), it almost always refers to a three-phase network and three-phase motors, and usually induction motors. As to the impacts of motor drives on the supply network, they are primarily reflected in a voltage drop caused by heavy run-ups of electric motor drives. These dips occur in industrial networks or substation busbars of large industrial consumers. They are typically longer (more than 60 periods), and with a characteristic shape. Most commonly, the amplitude drop is not very large, but in certain situations it can be very serious. Figure 4 shows the flow of voltage change at a 6 kV bus at the run-up power induction motor (800 kW) of a coal mill in TPP Tuzla [7].

Consequences of voltage dips are particularly unfavorable for complex industrial production processes, which have a large number of regulated EMDs. In extreme cases, one of the worst consequences could be a shutdown.

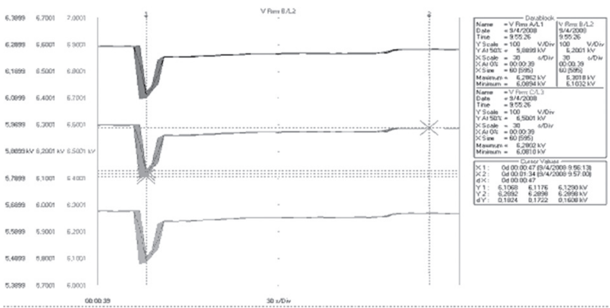

Fig. 4. Voltage drop at a run-up power induction motor (800 kW) of coal mill 2, block 6 in TPP Tuzla

A shutdown can occur in two places:

- in control-regulating circuits, based on electronics and microprocessors, and
- in relay protection circuits.

In these cases, electronic protection reacts in regulating circuits of the drive, which results in drive disconnection or process interruption. It can also cause electromagnet release in relays, contactors and other similar devices of relay protection and their failure. This creates substantial damage, which reflects not only in interrupted production, but also in the need to clear the production line of collected scrap and possible congestion.

The occurrence of voltage dips in the power system is inevitable and cannot be avoided. Therefore, it is necessary, to the fullest extent possible, to study their effects on various types of electrical equipment.

3.3. CONSEQUENCES OF THE ELECTRICAL PARAMETERS CHANGE AT START-UP

There are plenty of problems on electric drives with difficult start-up conditions. Some of the problems with the starting-up cage induction motors will be considered without going into all details. High-power cage induction motors have a relatively low starting torque. An increasing starting torque causes an increase in short-circuit currents that cause a significant voltage drop in weak networks. The engine torque is reduced by more than the square of voltage drop. If there is a large anti-torque of load, the motor does not have enough acceleration torque up to nominal speed and in this case protection would react. If there is no protection, the windings would be overheated and sustain damage [L.2.]. Large losses of energy in cage motor rotor windings at start-up are converted into heat, which is partially transferred to the stator windings. Because of large rotor heating, stress occurs that could cause damage to rotor windings, especially on the junction point between the rod and the ring. The reason for this is reduced heat dissipation as compared to the part located in the rotor iron sheet package, which leads to large lengthening of some rods. With construction of rotors which are not adequately manufactured, the consequence may be a defect on the junction between the rod and the short-circuit ring.

3.4. FAILURES IN LARGE 6 kV CAGE INDUCTION MOTORS

By applying a compact system for stator windings insulation, high operating safety is achieved and the possibility of failure in stator windings of 6 kV cage induction motors is virtually excluded. The aforementioned system of insulation yields high mechanical strength of winding heads and there is no fear of malfunction even under extreme conditions of motor start-up. While starting-up in difficult conditions, cage motor rotor windings are most likely to be harmed because a large amount of energy losses in rotor windings is converted to heat that leads to overheating.

Generally, all run-ups that last longer than 10 seconds are considered to be heavy run-ups. High material stress in the heavy run-up leads to damage of poor quality and improperly sized cage rotors. Cage windings of induction motors are exposed to centrifugal, thermal and electromagnetic forces. In relation to that, thermal stress on the material the cage is made of plays a crucial role.

During the launch, some parts of rotor windings are heated differently. Depending on the construction of rotor windings, that are mostly designed with deep rotor rods in order to achieve specific characteristics of a motor torque, some extent of current suppression in rotor cage rods occurs during the start-up. Current suppression will change from its maximum amount at slip s=1 to a negligible amount at nominal slip s_n. For illustration, it is the case where during the start-up resistance of exterior rod parts is higher and higher resistance causes greater warming. Considering the length of rods, greater warming of external sides of rods will lead to rod deformation. Furthermore, deformation causes the stress which may result in cracking and damage.

The most common defects are at the junction points of rods with short-circuit rings (Figure 5), because those places suffer superimposed stresses caused by an increase in the ring diameter due to warming.

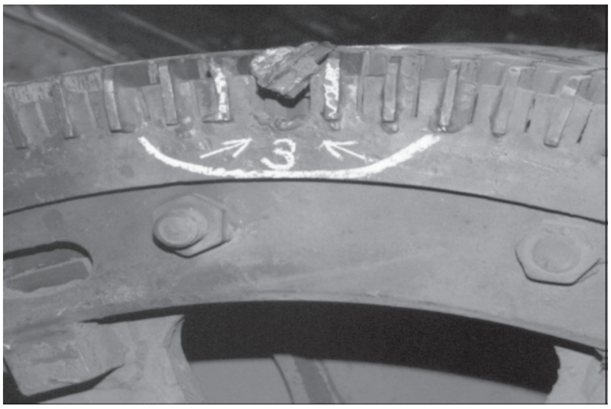

Fig.5. Example of HV motor cage damage (rod link with the short-circuit ring)

Such defects and malfunctions of rotors are particularly emphasized in motors with double cage rotors and especially if both cages are connected with one short-circuit ring. In double cage rotors, the upper rods are typically thin and made of the material with high specific resistance. Such design is necessary in order to achieve lower short-circuit currents and a higher torque. During the start-up, the effect of the upper cage is important and since it has small mass, its rods will sustain intense heat. The problem is even greater when the rods are inserted, thus extraction of heat from rods to the rotor iron sheet package is reduced.

It is possible to reduce the differences in warming of individual parts of the cage winding by using specific forms of rotor rods and slots. If rotor rods are tightly pressed against the iron sheet package surface, heat extraction is good and heating of rods is reduced. For this reason, trapezoidal rods that fit firmly on the iron surface are designed. Otherwise, because of the effect of current suppression mentioned earlier, the upper part of the rod is heated more. Elasticity of the rod from the iron sheet package to a short-circuit ring is achieved by the expansion of slots at ends of the iron sheet package. Full elasticity of the rod could also be achieved by using the braid; however, it is a very expensive and very complicated solution. Nowadays, simple rotors with minimized damage risk are produced.

Ring and rods are unevenly heated during motor run-up, because only parts of rods within the iron sheet package transfer their heat to the iron sheet package. However, parts of rods positioned outside of the iron sheet package, adjacent to the short-circuit ring, have only surrounding air to transfer heat to. Since upper parts of rods are cooled to a lesser extent than parts of rods within the iron sheet package, this creates unequal stretching in axial direction that leads to a loose rotor iron sheet package and rods cracking or their detachment from the ring. Thermal stress on rod ends is especially emphasized on well-fixed cages. If the iron sheet package is not well stacked and fixed and if rods are not installed with the greatest attention, especially in high speed engines, cracking or deformation of end plates on tooth bottom might occur. Torn pieces of metal can hit stator winding at high speed and cause damage. On hard brazed cages, considerable corrosion can also occur. Both, cage and brazing materials are not stable under the influence of aggressive environment.

3.5. DAMAGE TO THE SHORT-CIRCUIT CAGE IN DRIVE

As previously stated, cage induction motors are frequently used for drives with heavy start-ups, large inertia masses and a large anti-torque of the operating mechanism. In relation to that, thermal stress of the material the cage is made from plays a crucial role. Stresses that arise depend largely on the design of the cage. It is particularly so on rotors with long rods, which have an emphasized effect of current suppression. On such rotors, uneven distribution of current and losses in rods and short-circuit rings causes stress and deformation which, along with thermal stretching of the material, lead to cracking of rods and soldered parts of the cage. If the rod is not firmly placed in the slot, an alternating effect of electromagnetic forces creates oscillating deformation that causes material fatigue and ultimately rod breaking. In each brazing (700-800 °C), copper changes its properties. It leads to recrystallization, thereby reducing strength of hard drawn materials. Short-circuit rings and rod ends are exposed to this annealing process in the case of brazing. Another cause that leads to changes in properties of copper is copper disease that occurs in copper containing oxygen and when using the soldering flame. Vibrations cause formation of electric arcs and generally gradual burning of the rotor iron sheet package. Since electromagnetic forces increase with the square of current, they are at the greatest level at the engine start-up. Cracked short-circuit rings are relatively rare, but they can occur. Their breakage is usually a result of an already cracked solder [3].

Timely detection of the failure provides great advantages in the drive, because it allows planning and preparation of repairs at the most convenient time for operation, before complete shutdown occurs. For this reason, it is desirable to detect a defect on the rod or the ring as it occurs. Damage to the rotor shown in Figure 6 can be detected by a new, high-quality and cost-effective method of testing.

Fig. 6. Defective rotor of a 250kW engine

Damage to short-circuit rings is a result of thermal and centrifugal stretching that overloads ring material and causes small plastic deformations of the ring. In case the ring does not return to its original form after overload, it is constantly growing and increasing its diameter over time. Breakage due to material fatigue is typically a result of electromagnetic forces. This damage often occurs along the entire length of the rod, and the rod frequently breaks on several places. This kind of damage is not easily visible, thus it is difficult to detect. Rod stress due to electromagnetic forces heavily depends on how the rod fits in the slot. If rods movement in slots is prevented in axial direction, electromagnetic forces have a lesser effect. If rod breakage or detachment of the rod from the ring occurs due to increased thermal stress, it leads to the fracture and detachment of adjacent rods. The free end of the rod could be additionally deformed due to centrifugal forces and could mechanically damage the stator winding, causing a complete destruction of motor windings.

In the production phase and during the repairs, it is particularly important to control the quality of soldered or welded places between the rod and the ring of the rotor. In addition, it is essential to determine the conductivity of both replaced and old rods. This could be very important because there are often rod cracks in the rotor itself that are hardly visible to the naked eye. Special attention must be paid to cracks in rods, rings and links between rods and rings. In the area of cracks or breakages, the flow of current is reduced due to increased resistance, but besides that, due to a large increase in electrical resistance, such places generate a large amount of heat. Disruption of the rod or contact causes currents between the adjacent rods to close between the teeth of the rotor iron sheet package. Due to strong local heating, the surface of the rotor in such places becomes blue, brown or yellow. Since the electrical conductivity of all rods in the same cage is equal, the measured discrepancies in the conductivity are caused by uneven rod-ring contact resistance. In this way, the condition and the quality of welds on a cage can be inspected very efficiently and accurately. As all rods must have the same electrical conductivity, it is logical that cracked or broken rods will differ from others as far as electrical conductivity is concerned. This can be used to determine the condition of a cage or a rotor.

Non-homogeneous welds and welds with an insufficient amount of material have increased rod-ring contact resistance. In very good rotors, conductivity deviation of individual rods should be approximately within the range of ± 5% of the average value of all cage rods, and in still usable cage rotors, conductivity of individual rods should be within ±10%.

Detected deficiencies are mainly eliminated by replacing the entire cage on a rotor, unless the problem is the quality of connection between the rod and the ring, which can be quickly and easily fixed by brazing or welding the same.

4. CONCLUSION

The analysis conducted in this paper aimed to update the issues of failures and their causes on the rotor of HV cage induction motors. High-voltage cage induction motors are almost typically part of heavy EMDs in production processes that are very often the main EMD as well, because their operation is required for the operation of many other EMDs. In relation to that, timely detection of motor failure is of great importance, especially to avoid potentially expensive delays in the production process. Based on the analysis, it can be concluded that the windings of large electric motors in dynamic engage mode and at restarting are subject to high stresses. The reason for this is that theoretically double surge short circuit currents could occur, and since the force is proportional to the square of current, electric motors windings will sustain the quadruple stress force. Deformations that may take place in an electric motor by the influence of the aforementioned forces are undesirable, not only for electric motors, but also for the electric motor drive as a whole. Geometrical configuration of winding heads on the electric motor influences formation of these defects as well. Namely, on electric motors with larger head coil length and greater strength, deformation happens faster than on electric motors with less power (smaller length of the coil head). Finally, the necessity of regular preventive maintenance should be emphasized in order to avoid unwanted damage and shutdown of the entire production process.

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