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DERATING OF THREE-PHASE SQUIRREL-CAGE INDUCTION MOTOR UNDER BROKEN BARS FAULT [*]

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Abstract. *This paper addresses derating of a three-phase squirrel-cage induction motor under rotor broken bars fault. For this purpose, a winding function based analytical model is used. Different types of effective losses including core losses and Ohmic losses are estimated using a full analytical method. The relationship between the induction motor losses and load is determined and it is shown that the core losses, known as the constant losses in the motor, vary with load. A proper function based on the induced electromotive force (emf), Steinmetz coefficients and load level are introduced to show variations of losses with the induction motor load. Finally, derating is applied assuming that the motor losses in all cases must be equal to that of the healthy induction motor.*

Key words: *Broken bars fault, Derating, Induction motor, Losses estimation*

1. INTRODUCTION

Life span of electrical apparatus depends on their losses, therefore estimation of the losses is one of the most important factors in the design of electrical machines. In the case of a continuous operation of squirrel-cage induction motor (SCIM) in product lines, their losses must be continuously estimated. The losses in electrical machines include stator copper losses, rotor Ohmic losses, stray load losses, core losses and windage and friction loses. Fig 1 shows typical fraction of losses in a 4-pole, 50 Hz induction motors (IMs) over different power ratings [1]. It indicates the importance of the above-mentioned

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losses. Generally, their relative importance depends on the motor size. For simulated 11 kW IM, stator and rotor Ohmic losses have more contribution in the total losses of the motor. Any electrical machine is designed for a particular range of losses. Heat losses in different parts of machine are increased by the increase of the total losses and this has negative impact on the insulation of the machine. If the losses of the machine exceed the permissible values, the insulation system deteriorates and consequently the machine is not usable [2]. The increase of the losses leads to a shorter life of the machine and may disturb the product line. In case of a fault, the load of the machine must be reduced and this is called derating. In recent years, researches have focused on the derating of SCIM under unbalanced supply voltage.

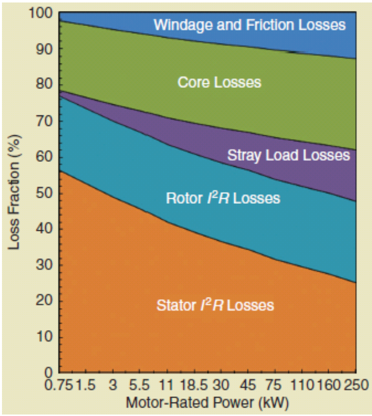

Fig. 1 Typical fraction of losses in 4-pole, 50 Hz, induction machine [1].

In [3], impacts of different unbalanced supply voltage such as over-voltage or under-voltage upon the SCIM performance have been studied and derating factors for each case have been given based on the National Electrical Manufacturers Association (NEMA) standard. NEMA derating curves have been provided for over-voltage and under-voltage cases, and then the motor losses and temperature rise have been determined using electrical and thermal modelling.

Non-linear load causes additional losses in transformers. IEEE C57-110 standard considers the transformer loading under asymmetrical current. This standard can determine the trend of determining the transformer loading under non-sinusoidal current [4].

One of the most important parts in the performance analysis of SCIM is the definition of a voltage-unbalanced factor. Derating of SCIM under complex voltage unbalance condition was introduced in [5]. Complex unbalanced voltage is the condition in which both magnitude and phase angle of the voltage are unbalanced.

There is a more complicated case where, in addition to the unbalanced voltage, there exist unbalanced and non-linear load; this is called a mixed derating. This mixed derating was applied to a transformer [6] and it was shown that the unbalanced voltage increases both copper and core losses in the transformer, while non-linear load can only increase copper losses.

According to IEEE 519 standard, for voltage harmonic content higher than 5% in IM, derating must be applied [7]. At this end, derating of an IM with no slot skewing, Δ-connected stator windings and non-earthed neutral has been investigated in steady-state mode using superposition. This method studies the derating of IM based on electrical equivalent circuit and a simple thermal model of the motor.

To improve the linear equivalent circuit of IM, the impact of the magnetic saturation and temperature rise upon the parameters of the IM have been included. The increase of loading capacity of a three-phase SCIM with unbalanced supply in over-voltage and under-voltage cases was considered in [8]. Furthermore, the impacts of unbalanced phase on the derating factor of IM were included. The derating factors obtained from the two methods were compared and after applying the derating factors, the results consisting of current and temperature rise were compared. For thermal analysis of IM a non-linear thermal model was used in [8]. For instance, at the same conditions, machine with lower saturation level has smaller derating factor compared to that of the higher-level saturation.

The further step in the derating of SCIM is consideration of internal fault in the machine which rises the losses in the motor. There are different internal faults in SCIM, which have been so far investigated by many researchers. However, less attention has been paid to the motor losses and particularly its derating in the presence of these faults. One of the common faults particularly in industrial IMs, is the rotor broken bars fault.

This paper investigates the derating and impact of load upon the core losses in SCIM. An equation is obtained to show the variations of the core losses with the load. The derating factors versus fault degree are estimated and finally the impact of broken bars upon the life span of SCIM from losses point of view is investigated.

2. EFFECTS OF HEAT ON ELECTRICAL MACHINES

According to NEMA MG-1 standard, 1% unbalanced voltage results in 6% unbalanced current in the machine. This leads to higher losses, temperature rise, and shorter life span of the machine. Furthermore, these unbalances generate larger ripples on the speed and torque which are undesirable. In addition, the load level affects the level of damages due to the unbalanced voltage [9].

In a full-load SCIM, the winding temperature is around 120ºC, the Ohmic losses are 30% of the total losses [10] with 20 years life span. 1% unbalanced voltage leads to the winding temperature of 130ºC, Ohmic losses of 33% and 10% life lose of the motor. 5% unbalanced voltage results in the winding temperature of 185ºC, Ohmic losses of 45% which reduce the motor life span to 1 year. 6.35% unbalanced voltage leads to 50% increase in the losses and 23% reduction in the developed torque of the motor [11]. Furthermore, the rate of temperature rise in SCIM is twice the rate of increase of the unbalanced current. This temperature rise enhances the windings resistance, which causes the increase of the losses in the machine [12].

Fig. 2 shows the impact of the unbalanced voltage on the winding temperature rise, winding Ohmic losses, efficiency reduction and life expectancy of the` SCIM [10]. The temperature rise of SCIM will be higher than that of the permissible value when the unbalanced phase voltages are applied. This excessive heating is mainly due to the negative-sequence current attempting to run the motor opposite to the normal direction.

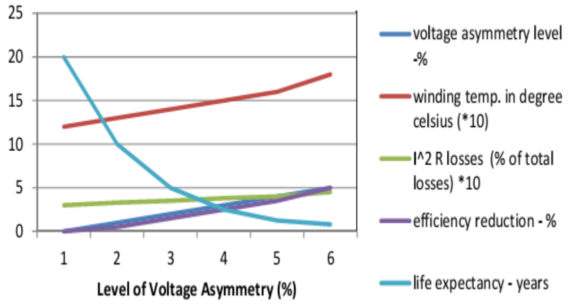

Fig. 2 Negative impacts of unbalanced voltage upon induction motor performance [10].

This higher temperature results in degradation of motor insulation and shortened motor life [13].

The basic relationship between the life of insulation materials and the absolute temperature is as follows:

$$L = B\exp\left[\frac{\varphi}{KT}\right]. \tag{1}$$

where L is the life unit of time, B is the constant factor determined experimentally, φ is the activation energy (in ev), T is the absolute temperature (in ºK) and k=0.8617×10^{-4} (ev/ºK) is the Boltzman constant. Fig. 3 shows the insulation life versus absolute temperature.

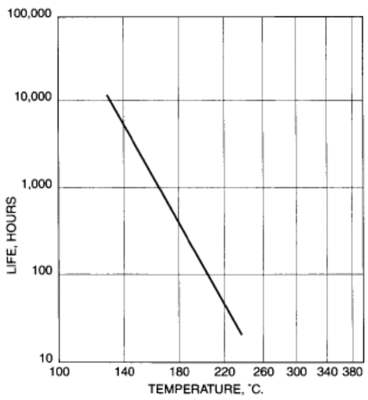

Fig. 3 Arrhenius plot for a typical insulation system [14].

3. EXPERIMENTAL SETUP

Generally three stages must be followed in the derating estimation of SCIM under rotor broken bars. The first is determining the impact of rotor broken bars on the different losses of SCIM including core and Ohmic losses. The second stage is the estimation of the impact of the load changes upon these losses. Finally, the derating factor is estimated.

An Industrial 11 kW 3-phase, 380 V, Δ-connected, 50 Hz and 4-pole and 24 A SCIM has been proposed for estimation of its derating. The rotor includes 28 Al bars with the slot skew angle equal to 0.225 rad. over the arc length. Table I shows the simulated IMs parameters. In order to verify the model, the results are compared with experimental results. To study different rotor broken bars cases, a number of holes is created in the middle of rotor bars so that the bar is fully destroyed (Fig. 4). To determine the losses in SCIM, no load, locked rotor and DC tests are carried according to IEEE12 standard.

Table 1 Parameters of simulated SCIM

Rated power	11kW
No. of stator slots	36
No. of rotor bars	28
Stator winding resistance	0.87Ω
Stator leakage inductance	4.3mH
Rotor bar resistance	45μΩ
Rotor end ring resistance	3.5 μΩ

Fig. 4 A rotor with one fully broken bar.

4. Impact of Rotor Broken Bars Fault on Different Types of Losses

The proposed SCIM modeled by winding function method (WFM) has been described in [15, 16]. The skewed slots of rotor, saturation and local saturation are included in WFM to enhance the accuracy of the model. Rotor broken bars fault has no similar impact on different types of losses in SCIM. This fault causes the core losses raise which is a consequence of local saturation. When the rotor bar is damaged, its current flows through adjacent bars and causes the rise and fall of the current in some of them. This results in asymmetry of the magnetic field. Asymmetric magnetic field in the rotor broken bar region (around the bar with higher current) leads to the magnetic saturation. This saturation does not cover the whole part of IM and occurs in particular regions of the rotor, stator cores and the air gap; it is called local saturation which has several effects. The most important one is its impact on the location of the hot spot within the core. In addition, saturation increases the core losses. To calculate core losses for non-sinusoidal magnetic fields, there are several analytical and numerical methods. Here, an analytical method based on the modified Steinmetz equation is used [15, 16].

This fault also increases the stator Ohmic loss due to the more stator current harmonic content. The current of the broken bar passes its adjacent bars and this itself causes the rise and fall of the current of some bars and this ultimately slightly decreases the Ohmic loss of rotors bars. The end ring current increases as a result of bars breakage and this increases the end ring Ohmic losses. The drop of Ohmic losses of rotor bars is more than the rise of the end ring Ohmic losses; as a result, the total rotor Ohmic losses drop. Fig. 5 shows the impact of the rotor broken bars fault on the core losses, stator Ohmic losses, rotor Ohmic losses and the total losses of SCIM for different number of broken bars (NBB). As expected, core losses and stator Ohmic losses increase and rotor Ohmic losses decrease as a result of NBB rising. Fig. 5d shows that the total losses of SCIM increase as a result of NBB increases. It shows that core losses and Ohmic losses rise are more than the rotor Ohmic losses fall. Also, the experimental results are close to the simulation results and this verifies the SCIM model.

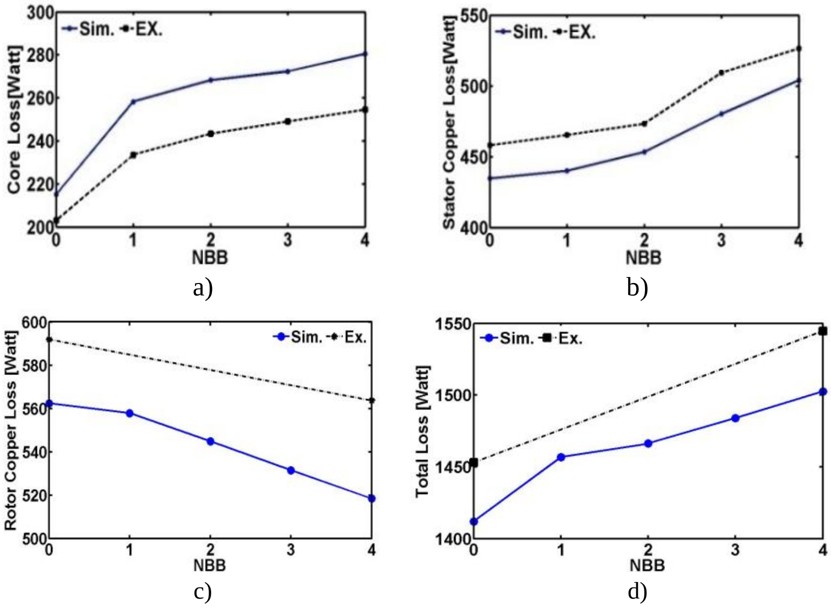

Fig. 5 Impact of rotor broken bars on: (a) core losses, (b) stator Ohmic losses (c) rotor Ohmic losses and (d) motor total losses.

5. Impact of Load on SCIM Losses

Losses are categorized into fixed and variable losses. It means that the fixed losses do not depend on the load. However, the fixed losses have approximated relation with the load. In fact, these losses vary with load, but, its variation is negligible. To enhance the accuracy of the losses estimation, variations with load must be taken into account.

In any operating conditions of SCIM, core losses are estimated using the following conventional Steinmetz equations:

$$P_{core} = k_h f B_m^x + k_e f^2 B_m^2. \tag{2}$$

where P_{core} is the core losses, k_h, k_e and x are the Steinmetz coefficients and B_m is the peak of magnetic flux density The Steinmetz coefficient can be determined by having the maximum core losses curve for lamination 2212 (proposed motor core lamination) at frequencies 50 and 60 Hz (Fig. 6).

Based on the Faraday's law, Eqn. (2) can be rewritten as follows:

$$P_{core} = K_h f^{1-x} e_{\max}^{x} + K_e e_{\max}^{2}. \tag{3}$$

where K_h and K_e are the new Steinmetz coefficients and e_{max} is the maximum emf. The emf is obtained as follows:

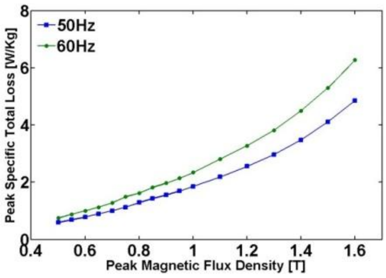

Fig. 6 Specific maximum losses curve of ferromagnetic sheets versus magnetic flux density for ferromagnetic sheet 2212.

$$e(t) = v_S(t) - R_S i_S(t) - l_{ls} \frac{di_S(t)}{dt}. \tag{4}$$

where v_s is the supply voltage, i_s is the stator current, R_s is the stator winding, l_{ls} is the stator phase leakage inductance. According to (4), emf depends on the stator current; on the other hand, the core losses depend on the maximum emf and load. Consequently, core losses depend on the current which varies with load. Fig. 7 shows the variations of core losses of the healthy SCIM with load.

According to Fig. 7, a lower load increases the core losses. The reason is that it depends on the emf amplitude. By increasing the load of SCIM, stator current amplitude rises and the peak emf will reduce based on (4). Fig. 7 shows that, to be able to define the core losses as a function of SCIM load, first, the induced emf must be obtained as a function of load. Since in (4), v_s, R_s and l_{ls} are constant, and i_s can be assumed almost sinusoidal, so:

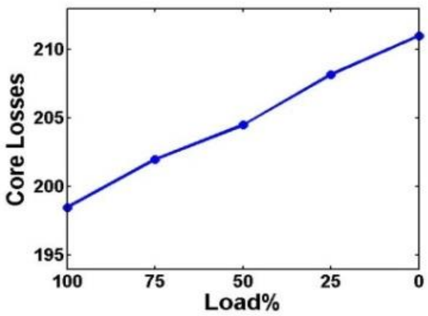

Fig. 7 Variations of core losses of healthy SCIM with load.

$$e \propto ay + b \tag{5}$$

where y indicates the load percentage compared to the rated load and a and b are the constant values. Considering (3) and (5), dependency of the core losses on SCIM load can be expressed as follows:

$$P_{core} = K_h f^{1-x}(ay+b)^x + K_e(ay+b)^2. \tag{6}$$

In other words, (6) shows a very precise variations of the stator core losses of SCIM with load under different operating conditions. Now, having the core losses in a particular SCIM over different loads (similar with Fig. 5), approximated curve on these points based on (6), coefficients a and b of (6) can be evaluated and a general equation for core losses under different loads are introduced.

6. Estimation of Derating Factor

There are different techniques to estimate derating. In the faulty line-start SCIM, the supply voltage has a perfect sinusoidal and balanced form, therefore, the derating factor versus voltage unbalanced cannot be applied. As a result, in this method, it is assumed that for optimal operation of SCIM, its total losses must be fixed [2,9] or:

$$P_{loss,nom} = K_h f^{1-x}(ay+b)^x + K_e(ay+b)^2 + y^2 P_{Ohmic,nom}. \tag{7}$$

where $P_{loss,nom}$ is the total losses in healthy SCIM and $P_{ohmic,nom}$ is the Ohmic losses of SCIM at the rated load. Since Ohmic losses are proportional with the square of the current and the current has direct relationship with the load, the Ohmic losses at any load are the product of the square of load (y) and rated Ohmic losses ($P_{ohmic,nom}$). Having all parameters, y is estimated according to the operation of the motor under special conditions. Difference between the estimated y with the full-load case shows derating. Fig.8 shows the derating factors for different NBB.

The derating factor in SCIM depends on the losses which rise by increasing the fault degree. Although it seems that the derating factor is small it has a large impact over long time. In broken bars fault, local saturation occurs and this leads to the increase of hot spot temperature within the motor which itself is the origin of different internal faults in SCIM.

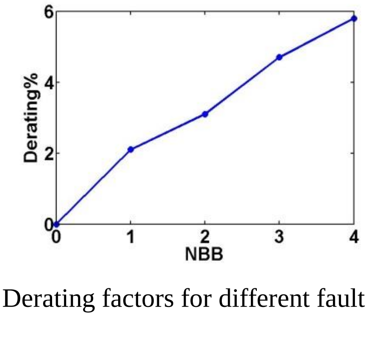

Fig. 8 Derating factors for different fault degrees.

7. Impact of Broken Bar Fault on Induction Motor Life Span

The increase of the losses in SCIM has direct impact on shortening the life span of the motor. Generally, broken bars fault causes higher losses, which shortens the lifespan of the motor. At this end, having the derating and using interpolation, % of the age reduction versus the NBB can be estimated according to Fig. 9. As seen in Fig. 9, one broken bar can shorten the life of the motor by 75%. This rises to 95% by 4 broken bars under a pole. So, in a motor with 20 years life, one broken bar reduces its life to 5 years and 4 broken bars to 1 year. It is noted that by passing the time, the fault degree increases which leads to a further shortening of the motor life.

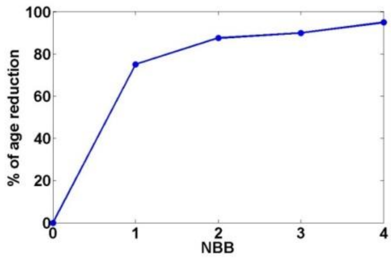

Fig. 9 Age reduction of induction motor (in %) versus NBB.

8. Conclusion

This paper studied the impact of the rotor broken bars fault on the SCIM. It was shown that the core losses and Ohmic losses rise by increasing the fault degree while the Ohmic losses decrease slightly. However, the total losses on the SCIM increase by increasing the number of the rotor broken bars. The relation between different losses in SCIM with load was determined and it was realized that the core losses are reduced by increasing the load. The core losses were taken into account and a very precise equation for core losses versus load was introduced. Derating for a faulty SCIM was estimated considering that the total losses of the faulty SCIM must not exceed the rated losses of the healthy machine. It was shown that the derating factor increases by increasing the number of the rotor broken bars and faulty motor must operate at lower load.

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