A Novel Analytical Method for Loss Calculation in Line-Start and Inverter-Fed Induction Motors under Broken Bars Fault

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Abstract — In this paper, a novel analytical approach is proposed to calculate ohmic and core losses in induction motors under breakage of the rotor bars. In order to precise loss computation, the non-sinusoidal characteristics of the distorted magnetic flux density and unbalanced stator currents due to the breakage bars are taken into account. Hence, new coefficients are defined and determined analytically to achieve new formula for ohmic and core losses estimation. Furthermore, considerable effects of inverter harmonics on the stator currents and magnetic flux density in the inverter-fed induction motor are reckoned for precise loss calculation in this case. Impacts of the different controlling strategies on the proposed approach are studied from different aspects. The necessary parameters and signals are simulated using modified winding function method as an analytical modeling method. The obtained results via proposed approach are verified by the finite element method and experimental results.

I. INTRODUCTION

Loss calculation in induction motors (IMs) is one of the most important aspects of this machine for designers and users in different industries. In the design procedure, motors losses are calculated for the normal conditions. This calculation is not valid for the abnormal conditions such as breakage broken bars. Protection, maintenance and optimal utilization of the IMs are subject to the accurate loss calculation in these motors. So, available methods for loss estimation in healthy IMs should be modified for faulty cases. The only published paper in this issue is [1] which has computed core losses and ohmic losses in IMs under eccentricity and broken bars faults using finite element method (FEM). It has been mentioned that broken bars raise core losses in IMs due to increase of magnitude of the harmonic components in the airgap flux density distribution. However in [1], portions of hysteresis and eddy currents losses have not been determined. In addition, IMs are utilized closed loop practically which has not been considered in [1]. Eventually, albeit FEM is a precise method for calculation, it needs many data for simulating motor whereas these data are not available for most of cases. It is obvious that performance analysis of the faulty IMs is the vital stage for maintaining IMs which has been investigated in many papers [2]. It has illustrated that broken bars magnify amplitude of the side-band components (ASBCs) at particular frequencies in the spectra of the speed, torque and stator currents of the faulty IMs. It has been exhibited that fault extension increases ASBCs in the aforementioned signals considerably which magnifies motor noise. It has been concluded that motor performance quality decreases due to broken rotor bars.

II. CALCULATION OF CORE LOSSES IN LINE-START MODE

One of the simplest methods for core loss calculation in IMs is applying Steinmetz coefficients. In this method, hysteresis and eddy currents losses are estimated as follows:

$$P_{hystersis} = k_h f_s B_m^x \tag{1}$$

$$P_{eddy} = k_e f_s{}^2 B_m^2 \tag{2}$$

where P_h is the hysteresis losses, k_h, k_e and x are the constant Steinmetz coefficient, f_s is the supply frequency, B_m is the maximum value of the flux density and P_{eddy} is the eddy current losses. Among these parameters, the f_s is known and k_h, k_e and x may be obtained by manufacturer company. However, B_m should be calculated. The instantaneous magnetic flux density in IMs is determined by:

$$B(t) = \frac{1}{N_s A_{eff}} \int e(t)dt \tag{3}$$

where N_s is number of stator windings, A_{eff} is the efficient section of the magnetic core, e is the electromotive force (EMF) and t is the time. In addition, EMF is calculated as follows:

$$e(t) = V_s(t) - R_s i(t)_s - L_{ss} i_s(t) \tag{4}$$

where v_s is the stator supply voltage, r_s is the stator resistance and L_{ss} is the stator inductance. Stator currents and inductance are calculated by the winding function method (WFM) [3] which has been utilized for simulating motor performance. Fig. 1 depicts the spectra of the magnetic flux density in the healthy and different faulty cases. It is seen that fault occurrence and its extension increase amplitude of the side-band components at frequencies $(1\pm 2ks)f_s$ which k is an integer number and s is the slip. If the supply voltage is alternating and the instantaneous voltage value of the fundamental harmonic has the exact signature of the instantaneous value of the supply voltage, the peak-to-peak value of the flux density is derived as follows:

$$B_{p-p} = \frac{1}{2N_s A_{eff}} \int_0^T |e(t)| dt \tag{5}$$

By considering E_{av} as the average rectified value of the EMF, the peak value of the flux density is calculated as follows:

$$B_m = \frac{E_{av}}{4N_s A_{eff}} T = \frac{1}{4N_s A_{eff}} \frac{E_{av}}{f_s} \tag{6}$$

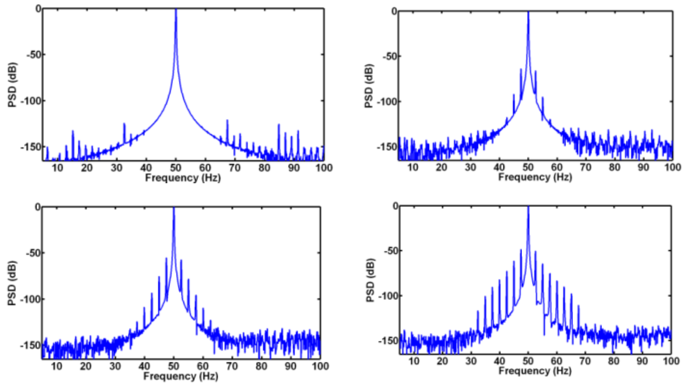

Fig.1. Spectra of the flux density of IM, (top, left) healthy, (top, right) 1 broken bar, (bottom, left) 2 broken bars and (bottom, right) 4 broken bars

By substituting (6) into (1), the hysteresis losses in IMs are determined by:

$$P_{hysteresis} = K_h f_s^{1-x} E_{av}^{x} \tag{7}$$

where K_h is the constant coefficient. The eddy current losses presented in (2) can be modified as follows:

$$P_{eddy} = k_e f_s^{2} \sum B_{n,\mathrm{m}}^{2} \tag{8}$$

where $B_{n,m}$ is the maximum value of the n^{th} harmonic component of the flux density. The value of the $B_{n,m}$ versus EMF is calculated as follows:

$$B_{n,\mathrm{m}} = \frac{E_{n,\mathrm{m}}}{n} \frac{1}{2\pi f_s N_s A_{eff}} \tag{9}$$

By substituting (9) into (8) and considering $E^2_{rms}=\sum E^2_{n,m}$, the eddy current losses are derived by:

$$P_{eddy} = K_e E_{rms}^{2} \tag{10}$$

Since breakage of the rotor bars distorts flux density waveform, here, correction factors are defined to calculate hysteresis and eddy current losses accurately. If the average and efficient values of the EMF for the healthy case are $E_{av,healthy}$ and $E_{rms,healthy}$, respectively, aforementioned values for the faulty cases are $E_{av,faulty}$ and $E_{rms,\ faulty}$, respectively. Consequently, the correction factors are determined as follows:

$$F_{av} = \frac{E_{av,healthy}}{E_{av,faulty}} \tag{11}$$

$$F_{rms} = \frac{E_{rms,healthy}}{E_{rms,faulty}} \tag{12}$$

Therefore, hysteresis and eddy current losses in the faulty cases versus healthy case are estimated by:

$$P_{hysteresis,faulty} = F_{av}^{x} P_{hysteresis,healthy} \tag{13}$$

$$P_{eddy,faulty} = F_{rms}^{2} P_{eddy,healthy} \tag{14}$$

Fig. 2 demonstrates the aforementioned losses for the healthy case and different number of broken bars. It is seen that breakage of the rotor bars increase hysteresis and eddy current losses. It is due to distortion of magnetic flux density which causes to raise side-band components in the flux density distribution which has been illustrated in Fig. 1.

III. Calculation of Ohmic Losses in Line-Start Mode

One of the employed approaches for ohmic losses estimation in IMs is determining the time average of the instantaneous ohmic losses in each winding. Since stator currents waveforms in the faulty IMs are modulated, and also the profile of the stator currents is different from one ac cycle to the next, this approach is appropriate for ohmic losses calculation in IMs. Therefore, the average value of the total ohmic losses under healthy and broken bars conditions are estimated using this approach. The instantaneous stator and rotor ohmic losses are illustrated as follows:

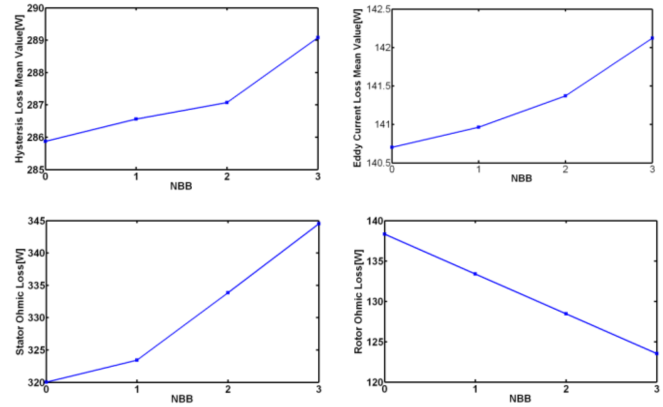

Fig.2. Losses variation of IM versus number of broken bars, (top, left) hysteresis losses, (top, right) eddy current losses, (bottom, left) stator ohmic losses and (bottom, right) rotor ohmic losses

$$P_{ohmic,s} = R_s\,(i_{s1}^2 + i_{s2}^2 + i_{s3}^2) \tag{13}$$

$$P_{ohmic,R} = \sum R_{r,n}\, i_{r,n}^2 \tag{14}$$

Where i_{s1}, i_{s2} and i_{s3} are the stator phase A, B and C instantaneous current values, respectively. Fig. 2 exhibits stator and rotor ohmic losses in the simulated IM by the WFM. It is seen that breakage of the rotor bars magnify stator ohmic losses. It is due to increase of harmonic components in the stator currents profiles [2]. Indeed, when rotor bars break, stator currents are distorted which causes to magnify harmonic components in the stator currents profiles. According to Fig. 2, rotor ohmic losses decrease in the faulty IM under broken bars. Because, when rotor bars break, their currents will be zero which will reduce rotor ohmic losses. Comparison of ohmic and core losses demonstrated in Fig.2 shows that incremental rate of the core losses and stator ohmic losses due to breakage of the rotor bars is more than that rotor ohmic losses. So, it is predicted that total losses increase in the faulty IM under broken bars.

IV. References

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