Energy Conversion and Management 52 (2011) 2024–2030

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Analysis of voltage unbalance effects on induction motors with open and closed slots

Pablo Donolo *, Guillermo Bossio, Cristian De Angelo

Grupo de Electrónica Aplicada, Fac. de Ingeniería, Universidad Nacional de Río Cuarto, Ruta Nac. #36 Km 601 (X5804BYA), Río Cuarto, Córdoba, Argentina

ARTICLE INFO

Article history:
Received 11 February 2010
Accepted 15 October 2010

Keywords:
Voltage unbalance
Induction motors
Derating factor

ABSTRACT

This paper aims to complement studies concerning the influence of voltage unbalance on the performance of induction motors. We use sequence equivalent circuits to determine the increase of losses in the induction motor. We take into account the dependence of the rotor negative-sequence reactance with the load state and the increase in rotor resistance with the negative-sequence currents. Variations in the negative-sequence impedance are related with the structural characteristics of the rotor. We analyze motors with open and closed rotor slots, because the impedance of rotors with closed slots grows considerably when the load is less than rated, producing lower negative-sequence currents and lower losses. Increased rotor impedance in closed slot motors protects these motors against problems due to unbalanced supply voltage. For both type of rotors, we analyze motor derating factor based on voltage unbalance and increases in total losses and rotor losses.

1. Introduction

Voltage unbalance affects the performance of induction motors (IM). Negative sequence voltages produce, in the air gap of the IM, a flux that rotates against the rotor's direction of rotation. This negative sequence flux produces torque pulsations, power pulsations, and highly unbalanced currents on the stator windings [1]. Torque and power oscillations result in increased vibrations [2] that may damage the IM [3]. Additionally, vibration due to voltage unbalance may be miss-attributed to bearing failure. Similarly, high negative-sequence currents may be miss-attributed to stator winding failure [4]. In these cases a healthy IM may be taken out service.

High negative-sequence currents cause overheating and hot spots in the stator windings of the IM [2]. To avoid overheating, the National Electrical Manufacturer Association (Standard NEMA MG 1-2003, revision 1-2004, Motors and Generators) and the International Electrotechnical Commission (IEC Standard 60034-1) provide derating factors for the output power that depend on voltage unbalance factors (k_v).

There are many papers discussing the limitations of these standards [1,5–7]. One of the troubles is that the voltage unbalance factors defined by the standards are non-injective. This means that different voltages may results in the same voltage unbalance factor.

Also, the derating factors defined by the standards are unique for all types of IM. This general definition may overprotect some IMs and may not be enough for others. Policarpo et al. [7] show that the derating factors of the output power set by the standards are too conservative, when the total losses of the IM are taken into account. On the other hand, Reineri et al. [8], provide an example where the derating factors are not enough to protect an IM with wound rotor.

Bibliography on voltage unbalance proposed different methods to estimate derating factors for IMs. In [9] the derating factors are obtained with the rated stator current of IM as the maximum allowable current. Wang [10] proposes using derating factors obtained in the same way but using complex voltage unbalanced factor. Gnacinski [11] proposed to determinate the maximum load in such a way that the windings temperature is limited to the value corresponding to rated working condition, but this method requires a very detailed model of the IM.

In this paper we propose a method to compute the IM's losses taking into account the effect of unbalanced voltages. To take into account the effect of voltage unbalance, we use a single phase equivalent circuit for the positive and negative sequences of the IM and we consider the skin effect in the sequence resistances of the rotor. The model also takes into account the negative-sequence reactance variations with IM's load.

The relationship between the negative-sequence impedance and the motor load depends on the rotor having open slots (OS) or closed slots (CS) [2,12].

IMs with closed-slot rotors have lower efficiency than IMs with open slot rotors but, they are widely used because they are simple to build.

At low load levels, when the iron on the rotor slots is not saturated, the negative-sequence impedance of closed-slot rotors is significantly larger than at rated load. We consider this effect

* Corresponding author.
E-mail addresses: pdonolo@gmail.com (P. Donolo), gbossio@ieee.org (G. Bossio), cdeangelo@ieee.org (C. De Angelo).

0196-8904/$ - see front matter © 2010 Elsevier Ltd All rights reserved.
doi:10.1016/j.enconman.2010.10.045

because IMs with closed rotor slots are widely used in medium and low voltage systems, in which power quality problems are more common.

2. Effects of unbalanced voltages on the IM

Voltage unbalance leads to large negative-sequence currents in the IM. Negative-sequence currents in IMs produce several adverse effects, such as increased copper losses in the stator and in the rotor, and oscillations in torque, speed and power.

Increased copper losses generate local temperature increases on the IM windings that lead to premature insulation failure. However, higher copper losses in the stator are not necessarily accompanied by a significant increase in stator currents and therefore cannot be detected by some overcurrent protections.

In the rotor, the problems are more severe because the negative-sequence resistance is greater than the positive-sequence resistance. This creates localized warming of the rotor circuits in a short period of time.

The negative-sequence resistance of the rotor is between 3 and 15 times greater than its positive-sequence resistance [13] because, the frequency of operation is almost two times the positive-sequence frequency.

For squirrel cage type rotors, the negative-sequence resistance is typically five times its positive-sequence resistance.

Depending on the structural characteristics of the IM, the negative-sequence reactance of the rotor may change significantly with the load.

In squirrel-cage rotors with open slots (Fig. 1a), the rotor negative-sequence reactance does not vary significantly because the leakage flux has a high reluctance path through the air for any loading condition of the IM.

In IMs with closed-slots squirrel-cage rotor (Fig. 1b) the iron that covers the bars is not saturated for low load levels. Thus for low load, leakage flux encounters a lower reluctance path than for rated load. These reluctance changes result in a larger rotor negative-sequence leakage reactance during low load conditions [2,12].

The different behavior of the rotor negative-sequence reactance with the state of load produces in the rotor with closed-slots smaller negative-sequence currents than in the case of rotor with open-slots. Then, a lower negative-sequence current produces a lesser increase of rotor losses.

Finally, the IMs with rotor windings, which have open rotor slots, are most affected by increased losses because the windings' insulation deteriorates with higher than normal temperatures.

3. IM model

3.1. Sequence equivalent models for IMs

In this analysis we considered the positive- and negative-sequences equivalent circuits of the IM [14]. These circuits allow analyzing the effects that voltage unbalance has on the IM [15,16].

The positive-sequence current defines the main rotating field and the direction of rotor rotation. The frequency of the positive-sequence current in the IM's rotor is given by ($s \cdot f$) where f is the supply frequency and s is the slip.

The positive-sequence equivalent circuit is shown in Fig. 2.

The frequency of the negative-sequence current in the IM's rotor is given by $(2 - s)f$. This negative-sequence current produces a field rotating against the main field. The negative-sequence field produces oscillations in the torque and power of the IM at twice the supply frequency. The negative-sequence equivalent circuit is shown in Fig. 3.

3.2. Equivalent circuit parameters

There are different ways to find the parameters of the IM [17–20] depending on the available data and equipment.

We obtained the parameters of two 5.5 kW IMs with squirrel-cage rotors using the no-load and locked-rotor tests [21]. One

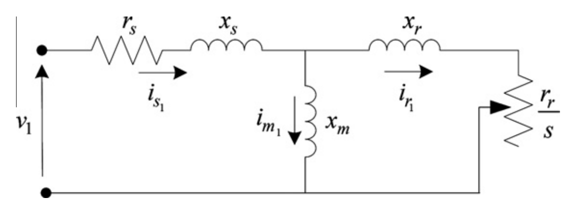

Fig. 2. Positive-sequence equivalent circuit.

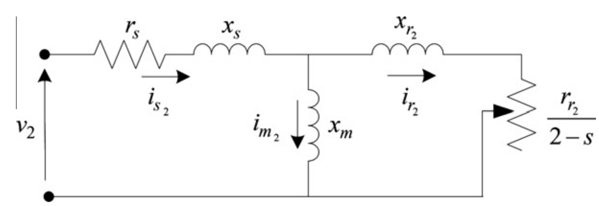

Fig. 3. Negative-sequence equivalent circuit.

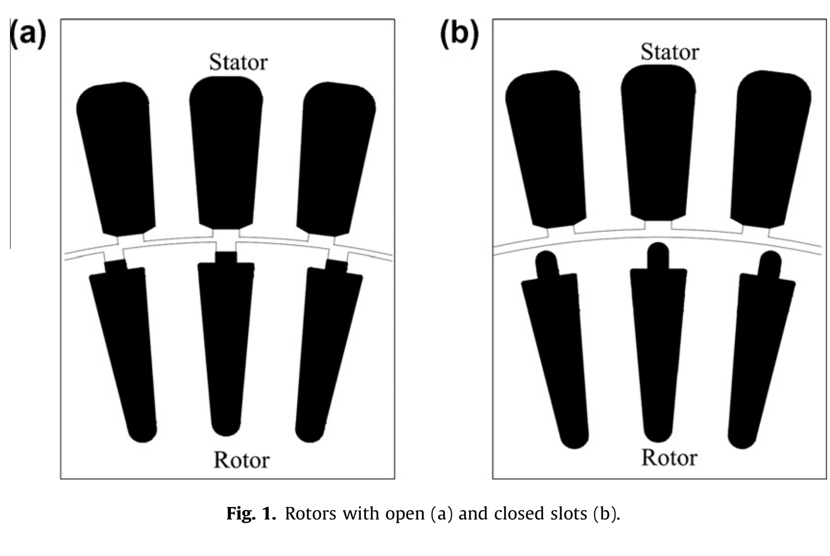

Fig. 1. Rotors with open (a) and closed slots (b).