



Influence of mixed winding arrangements on torque ripples of five-phase induction machines

Mbika Muteba, Dan Valentine Nicolae*

University of Johannesburg, Department of Electrical and Electronic Engineering Technology, PO Box 17011, Doornfontein, 2023, Johannesburg, South Africa

ARTICLE INFO

Article history:

Received 29 May 2016

Received in revised form 21 April 2017

Accepted 22 May 2017

Keywords:

Five-phase induction machines

Phase-belt

Torque ripple reduction

Winding combinations

ABSTRACT

In this paper, the authors take a particular look at the influence of mixed stator winding arrangements on torque ripple production in a 30 stator slots, 2-pole, and five-phase induction machine. The conventional five-phase double layer windings with 14/15 and 13/15 chorded coils are compared with the proposed five-phase mixed winding arrangements. This paper presents the design consideration and calculation of winding factors of the proposed mixed winding configurations. The different five-phase winding arrangements have been modelled using Finite Element Methods. The results obtained from simulation are compared to those obtained from experimental measurements. Both simulation and practical results have proven that the combination of double and triple layer winding, mixed with coil side shift to other layer, has tremendously reduced the torque ripple factor while maintaining the torque average.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The airgap field distribution in induction machines (IMs) is influenced by the stator and rotor magneto-motive force (MMF) distribution, magnetic saturation in stator and rotor teeth, and back-iron cores. The placement of windings in slots leads to a stepped-like waveform of the stator or rotor MMFs which exhibit space harmonics [1]. Most electric machine designs rely on the fundamental flux wave theory. Attention is concentrated on the achievement of sinusoidal flux density in the airgap with as little harmonic content as possible. The fundamental component of resultant airgap flux density distribution in interaction with the fundamental of stator or rotor MMF produces the fundamental electromagnetic torque in IMs [1].

However, very early IMs had two phases, but the three-phase version very soon replaced these, and this eliminated the third harmonic problems associated with two-phases and resulted in a motor that was generally better in all performance aspects [2]. Increasing the number of phases beyond three, though may be costly, has advantages which might be worth considering for certain special applications [3]. Among the advantages of machines with more than three-phases are to improve the shape of the fundamental flux wave by eliminating significantly some space har-

monics, to reduce torque ripples and rotor harmonic power loss for inverter supply motors, and to improve reliability since loss of one of many phases does not prevent the motor from starting and running [4–9].

The torque ripple results from the fact that discreet spatial distribution of windings does not produce an exact sinusoidal magneto motive force (MMF). The actual MMF wave contains significant number of higher order space harmonics. Their presence results in torque ripple that varies as a function of the number of slots. These space harmonics are commonly called slot harmonics. Another source of torque ripple is due to saturation of the magnetic material [10]. Previous research has shown that the torque ripple could be eliminated to a certain extent by short pitching the winding, by typically one or two slots to reduce lower-order MMF space harmonics [11]. Although this method has proved itself worthy but it was limited to coil chording of conventional double-layer windings and slot skewing.

In this paper the authors look at possible combination of different winding configurations and their influence on the torque ripple. Though the study is limited to a particular five-phase machine, the approach is valid for any m -phase IM of p -number of poles with integer number of slots per pole and per phase. It should be also noted that part of this work presented in this paper is well detailed in Ref. [12].

However, the winding configurations do not affect the slot harmonics but have an impact on phase-belt harmonics which depend on the placement of conductors under different phase-belts. Before

* Corresponding author.

E-mail addresses: mmuteba@uj.ac.za (M. Muteba), dnicolae@uj.ac.za (D.V. Nicolae).

proceeding further, the following assumptions are taken into consideration.

- Only the space phase-belt primary sequence harmonics are investigated.
- The machine is considered to be operating in steady state condition.
- Saturation effects are neglected, thus the space harmonics produced by leakage saturation and saturation of main flux are not considered.
- Effects of slot stator and rotor slot openings are neglected.
- The five-phase stators current are assumed to be sinusoidal.

2. Phase-belt harmonics

For five-phase symmetrical windings with integer number of slots per pole and phase, even order harmonics are zero and multiples of five are also zero. The existence of “ n ” primary sequence and secondary sequence order space harmonics and their direction of rotation in the air-gap of the five-phase induction machine are found as in (1) and (2) respectively [13].

$$n = 10k_j + 1 \quad (1)$$

$$n = 5k_i + 2 \quad (2)$$

Where k_j is any positive or negative integer and k_i is any positive and negative odd number but not zero. The primary sequence space harmonic orders are of order 1, –9, 11, –19, 21, –29, 31 ... and secondary sequence space harmonics orders are of order –3, 7, –13, 17, –23, 27 ... The negative sign indicates the backward direction of rotation respect to the fundamental MMF.

The space harmonics that are investigated in this paper are due to both placement of conductors in slots and placement of various phases as phase belts under each pole. In five-phase the phase belt spread is $\pi/5$ electrical radian (one fifth of a pole). The effect of stator and rotor slotting influence also on the MMF stepwise distribution [11] and are dependent on the number of slots in stator and rotor as indicated in (3) and (4). Let us note that the slot harmonics are not investigated in this paper but are only cited to give clear explanation about the phase-belt harmonics.

$$n_s = k(Q_s/p_1) + 1 \quad (3)$$

$$n_r = k(Q_r/p_1) + 1 \quad (4)$$

Where n_s and n_r are stator and rotor slots harmonics respectively. p_1 is the stator fundamental pole pair, Q_s and Q_r are the number of stator slots and rotor bars respectively.

It is important to note that the MMF harmonics whose order is lower than the first stator slot harmonics (Eq. (3)), are called phase belt harmonics. For a 2-pole, 30 stator slots, five-phase induction machine the first stator slot harmonic order is 29. The phase belt or phase band may be defined as the group of adjacent slots belonging to one phase under one pole. The angle subtended by one phase group $\sigma = q \times \alpha_s$, is called the phase spread angle, and it is totally dependent on the average number of slot per pole and phase “ q ” and the slot pitch angle $\alpha_s = (2p_1\tau)/Q_s$ (electrical radian). The slot pitch angle is directly proportional to the pole pitch “ τ ”.

The stator coil pitch “ y ” is normally chosen so as to reduce the lowest order phase belt harmonics which are generally largest [11]. It is important to note that the phase belt harmonics which can exist in the partial distribution of flux are those for which the harmonic order number “ n_p ” satisfies as in (5).

$$n_p = 2(\pi/\sigma)k_i + 1 \quad (5)$$

The first four phase belt primary sequence space harmonics order are therefore –9, 11, –19 and 21. Though saturation

Table 1
Special notations of winding configurations.

Notations	Description
DL-14/15	Double layer with $(y/\tau) = 14/15$ chorded coils
DL-13/15	Double layer with $(y/\tau) = 13/15$ chorded coils
DLCS-14/15	Double layer with coil side shift to other layer chorded by $(y/\tau) = 14/15$
DLCS-13/15	Double layer combined with coil side shift to other layer chorded by $(y/\tau) = 13/15$
DLCT-14/15	Double layer with coil side transferred to foreign zone chorded by $(y/\tau) = 14/15$
DLCT-13/15	Double layer with coil side transferred to foreign zone chorded by $(y/\tau) = 13/15$
DTL-14/15	Mix of double and triple layer with $(y/\tau) = 14/15$ chorded coils
DTL-13/15	Mix of double and triple layer with $(y/\tau) = 13/15$ chorded coils
DTLCS-13/15	Mix of double and triple layer with coil side shift chorded by $(y/\tau) = 13/15$

effects are neglected in this paper but one must note that in five-phase induction machine the most significant induction harmonic component that effectively produce the torque is the third one [6,14–16]. This harmonic field can be generated by saturation effect or current injection and it is part of set of secondary sequence space harmonics. These secondary sequence space harmonics are produced when stator windings are fed from an alternative sequence, feeding the winding with primary sequence will inherently cancel these harmonics [13].

3. Winding analysis

3.1. Basic single and double layer five phase windings

Conventional windings for poly-phase induction machines are layed out in one or two-layers in stator slots. The total number of coils equals half the number of stator slots for single layer configurations and equal to number of stator slots in double-layer configurations. Full-pitched and short-pitched coils are used depending on the application. Windings are built with integer or fractional slots per pole and per phase. In this paper only integer slots per pole and phase are investigated. Table 1 shows the notation of the different winding configurations analyzed in this paper.

Fig. 1 shows the double-layer with $(y/\tau) = 14/15$ chorded coils of a five-phase, 30 slots, two-pole induction machine. The harmonic distribution factor of a conventional single and double layer windings may be calculated as in (6), and Eq. (7) can be used to find the harmonic pitch factor of a chorded conventional double layer winding [17,22]. The harmonic winding factor is found by taking the product of (6) and (7).

$$K_{dn}^* = \frac{\sin nq(\alpha_s/2)}{q \sin n(\alpha_s/2)} \quad (6)$$

$$K_{pn}^* = \sin n(\pi y/2\tau) \quad (7)$$

3.2. Double layer windings with coil side shift to other layer

In this section, the authors present the double layer winding with coil side shift to other layer. The method consists of shifting in one pole pitch the lower layer of the coil with a coil side transfer to the upper layer and in the other pole pitch the upper layer of the coil is shifted with a coil side transfer to the lower layer as shown in Fig. 2. By doing so the winding configuration has a non-uniform coil group distribution in sequence order of “4 and 2”. It is clearly indicated that the distribution factor is calculated using the average number of slots per pole and per phase $q_{av} = (q_1 + q_2)/2$, where q_1

Download English Version:

<https://daneshyari.com/en/article/5001010>

Download Persian Version:

<https://daneshyari.com/article/5001010>

[Daneshyari.com](https://daneshyari.com)