Performance Analysis of Induction Machines With Unconventional Winding Configurations

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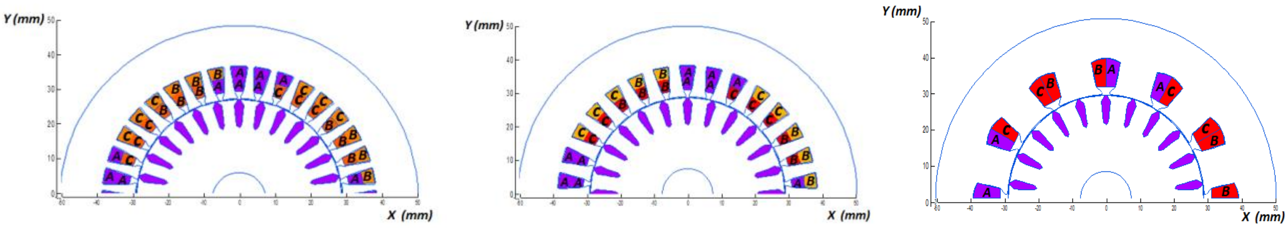
Abstract. This paper presents the performance of fractional slots distributed windings (FSDW) and fractional slots concentrated windings (FSCW) of three-phase squirrel cage induction machines. The different windings have been designed and modeled using the same machine physical and electrical parameters. The Finite Element Model (FEM) of the machine for the different windings has been carried out. The results for the machine with FSDW and FSCW are compared to the results of the conventional double layer (CDL) with 8/9 chorded coil.

Introduction

The search for more cost effective and fault tolerant layouts drives design of electrical machines up to its limits. Moreover, the requirements of many applications both in industry and in the field of renewable energy conversion are though that traditional layouts are abandoned in favor of new topologies or new light in shed over older one [1].

The three-phase induction machines commonly use double layer, overlap, distributed windings [2]. This winding configuration results in more sinusoidal magneto-motive force (MMF) distribution and electromotive force (EMF) distributions, and hence, good machine performance [2]. However, it utilizes bulky end windings and over lapping coils. On the other hand fractional concentrated windings (FSCW) have been gaining a lot of interest in Permanent Magnet (PM) synchronous machines. This is due to several advantages provided by this type of windings which include: shorter non-overlapping end turns, higher efficiency, higher power density, higher slot fill factor, lower manufacturing cost, better flux-weakening capability resulting in wider constant power speed range, and fault tolerance [3]. The application of this winding to induction machine is also gaining momentum and the performance of five-phase FSCW induction machine is analyzed in [2], and its application to linear induction machine is discussed in [4].



(a) (b) (c)

Fig.1 Three-phase squirrel cage induction machine phases distribution in slots.
(a) CDL- 8/9 chorded double layer winding, (b) FSDW double layer winding, (c) FSCW double layer winding.

However the low speed applications need always electrical machines with high number of poles in both cases of motors and generators. In the conventional wound machines the high pole number leads normally to a high slot number implying the disadvantage of low slot filling factor and increasing in the cost of manufacturing. The alternative of fractional-slot winding is to be considered in such application due to the simplicity of the winding manufacturing and reducing the amount of copper by less end winding length [3]. Even the fractional-slot windings have not necessary lower fundamental winding factor, they ever create upper space harmonics and sub-harmonics causing additional losses, extra heating, noise and vibration of the machines [4]. This is the reason why the fractional-slot winding machines have to be studied carefully especially when high power applications are in view such as wind energy direct driven induction generators.

Algorithmic method of design and analysis of FSDWs of multiphase AC machines is well illustrated in [5]. The design considerations and tradeoffs involved in applying FSCWs to five-phase induction machine using conventional three-phase lap wound machine as a reference is evaluated in [4].

Therefore this paper is focusing on analyzing the effects of FSDWs and FSCWs of three-phase induction machines on airgap flux density distribution, magnetic vector potential, rotor bar losses and electromagnetic torque. It should be noted that the machines operate under steady state conditions, there is no skew and the effect of saturation of the main magnetic flux in the stator teeth and rotor core are neglected. The machines under analysis are all 4-poles. The FSDW and FSCW are modeled with 30 and 12 stator slots, respectively. The CDL is modeled with 36 stator slots. A conventional three-phase squirrel cage, 3 kW, 4-pole induction machine parameters are used in FEM.

Problem description

In conventional winding configurations the symmetrical three-phase stator windings produce the MMF harmonics given by (1).

$$v = 1 \pm 6i\ , \qquad i = 0,1,2,3... \qquad (1)$$

The three-phase CDW will produce the MMF harmonics of order v = 1, -5, 7, -11, 13.... v_n

In induction machines, torque production depends on the interaction between the stator MMF and the rotor MMF produced by the induced rotor current. The MMF harmonic produced by the squirel cage rotor is given by (2).

$$v' = 1 \pm \frac{N_r}{p_1} j\ , \qquad j = 0,1,2,3... \qquad (2)$$

Where N_r is the total number of rotor bars and p_1 is the stator number of pole pair.

Hence, if the stator winding configuration is excited with certain frequency, a number of torque and rotor bar loss producing components are gererated at various slip because of the armature winding space harmonics. Some of these harmonics will produce positive torque, and others will produce negative torque. The resultant torque is the vector sum of individual torque components. Hence a poor torque density would normally accompanied by high torque ripple and excessive rotor bar and core losses .

While stator winding chording can be applied in a conventional lap wound induction machine to minimize the effect of winding space harmonics, the design option is not possible for FSCW. Such a limitation resulted in poor performance of three-phase FSCW induction machines as described in [2].

In FSDW the number of slots per pole and phase is denoted as in (3)

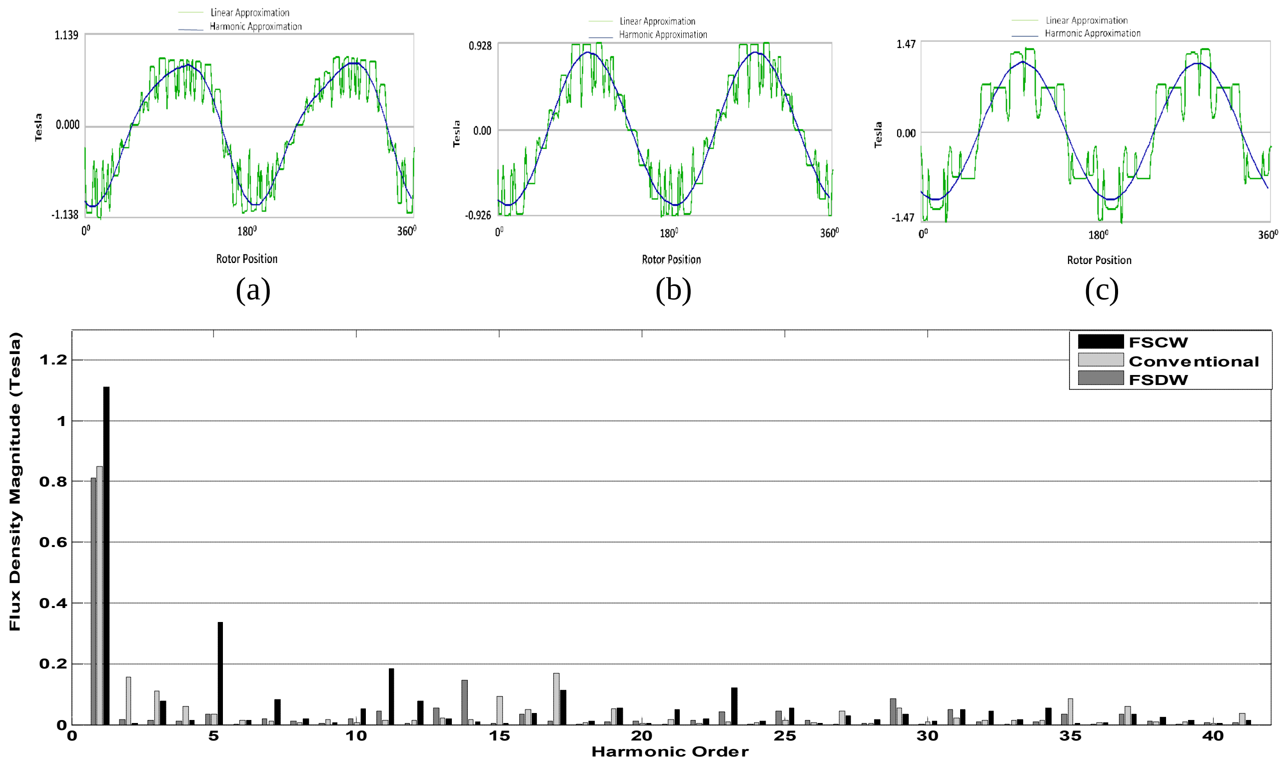
$$q = \frac{N_s}{2mq} = \frac{u}{h} = x + \frac{a}{b} \tag{3}$$

Where a, b- are the numerator and denominator of the reduced improper fraction , x is integer part of q, u and h are the numerator and denominator of the fraction characteristic of the winding.
The MMF harmonic produced by a FSDW is given as in (4) and (5).

$$v = j\frac{2p}{h} \;; \quad j = 1,2,3... \quad for \;\; h \;\; being \;\; even \tag{4}$$

$$v = j\frac{p}{h} \;; \quad j = 1,2,3... \quad for \;\; h \;\; being \;\; odd \tag{5}$$

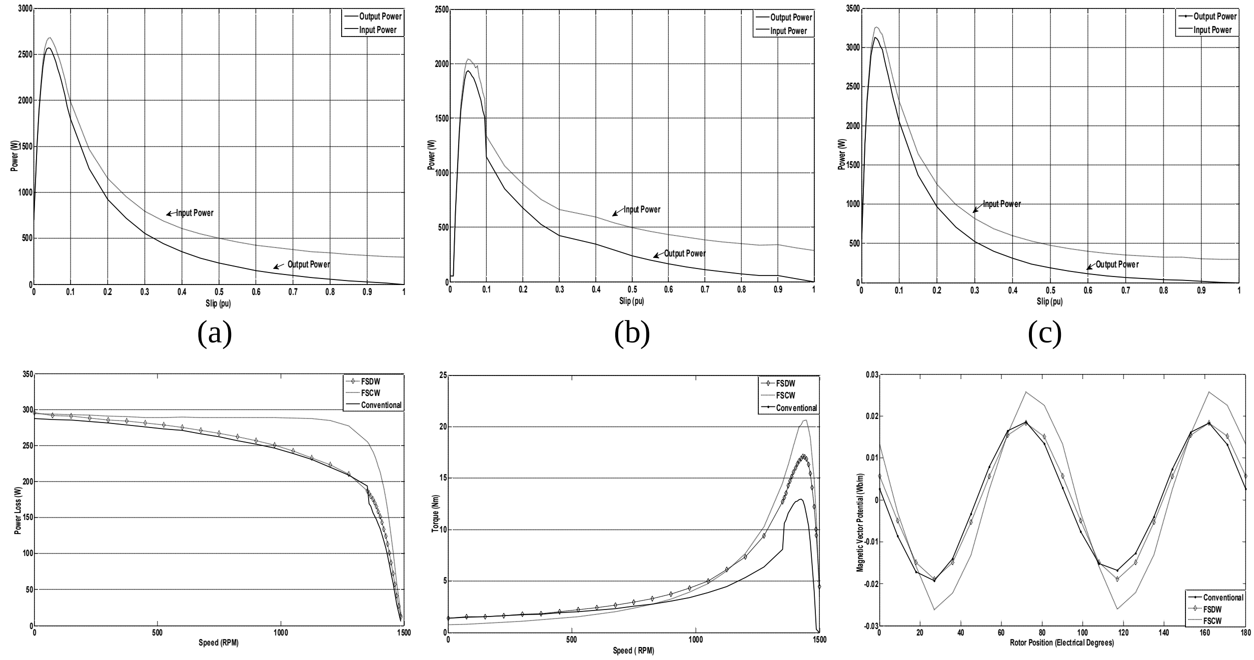
The flux-density in fig.2 a, b and c have been ploted from the mid air-gap of the machine and the harmonic spectra in fig.2 c has been obtained from Fast Fourier Transform (FFT). The slotting effects are very visible in all the plots. It is clear that the FSCW has a higher fundamental flux density compared to the FSDW and CDL 8/9. It is also noticeable from the FFT results that the first three phase-belts harmonics (v= 5, 7 and 11) are very dominent in FSCW. This is justified by the fact that the FSCW cannot be short pitched at all.



(d)

Fig.2 Mid-Airgap flux density and their harmonic spectra, (a) CDL- 8/9 chorded double layer winding, (b) FSDW double layer winding, (c) FSCW double layer winding, d) Fourier expansion of the airgap flux density distribution of (a), (b) and (c).

Observing from fig.3 g the FSCW has a higher magnetic vector potential which gives this winding the edge of producing a higher torque density. The effect of negative torque is quite visible in CDL-8/9 torque speed characteristic shown in fig.3 f.



(a) (b) (c)

(d) (f) (g)

Fig.3 a, b and c) Input and Output power as function of slip of FSDW double layer winding, CDL-8/9 chorded double layer winding and FSCW double layer winding, respectively, d) Comparison of rotor bar losses between FSDW, FSCW and CDL-8/9, f) Comparison of torque speed characteristic between FSDW, FSCW and CDL-8/9 and g) Comparison of magnetic vector potential between FSDW, FSCW and CDL-8/9.

Torque ripple

Electromagnetic torque shown in fig.4 a, b and c have has been computed from Maxwellôs stress tensor. This method requires only the local flux density distribution along a specific line or contour, then the torque can be calculated by means of the following expression:

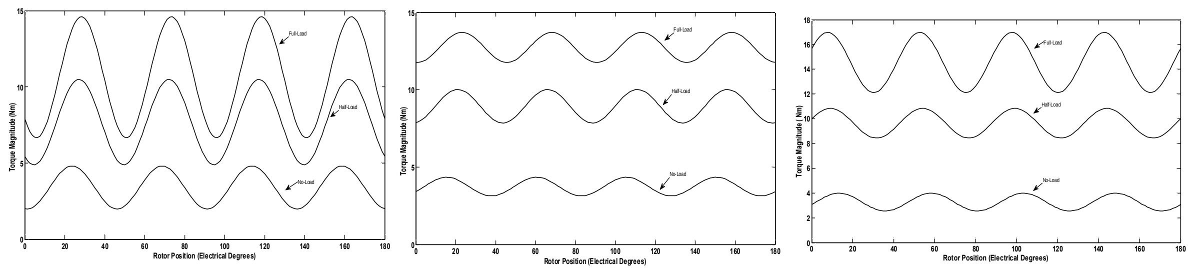
$$T_e = r\left(\sum \frac{1}{\mu_o} B_n B_t\, d\right) l \qquad (6)$$

Where B_n and B_t, are the normal and tangential components of the magnetic flux density, d is the length of the path between two consecutive nodes, r is the radius of the circular path taken and l is the axial length of the magnetic sheet core .The torque ripple factor can be defined as following:

$$T_{ripple} = \frac{T_{\max} - T_{\min}}{T_{av}} \times 100 \qquad (7)$$

Where T_{max}, T_{min} and T_{av} are defined as the maximum, minimum and average torque, respectively. Table I shows average values and torque ripple factors at different working conditions.

Reading from table I, it is quite clear that by employing the FSDW the torque ripple reduces tromendously from 74.73 % for the CDL-8/9 , down to 14.20 % while maintaining the torque average under full load conditions.



(a) (b) (c)

Fig.4 Electromagnetic torques at different loading conditions as function of rotor position. (a) Conventional three-phase 8/9 chorded double layer winding, (b) FSDW three-phase double layer winding, (c) FSCW three-phase double layer winding.

Table 1: Average torque and Torque ripple at different working conditions

Winding Configurations	No-Load		Half-Load		Full-Load	
	T_{av} [Nm]	T_{ripple} [%]	T_{av} [Nm]	T_{ripple}[%]	T_{av} [Nm]	T_{ripple} [%]
CDL -8/9	3.39	83.00	7.68	72.95	10.63	74.73
FSDW	3.74	32.14	8.92	24.24	12.72	14.20
FSCW	3.27	43.88	9.64	24.85	14.546	33.30

Conclusion

The performance analysis of three-phase induction machines with unconventional winding configurations has been carried out. It has been observed from results that the conventional double layer with 8/9 chorded winding has poor performance. It produces more rotor bar losses compare to the fractional-slots distributed winding and fractional-slots concentrated windings of the same physical and electrical parameters. These unconventional windings have minimized the torque ripple while maintaining the torque average. Though short pitching of the conventional double layer with one more slots to make it 7/9, will improve the airgap flux density distribution and minimize the torque ripple but this will drop the magnitude of fundamental flux density and thus will also drop the torque average.

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