Effect of Double-Triple Winding Layout on Axially-Laminated Anisotropic Rotor Synchronous Reluctance Motors

M. Muteba, *Member*, *IEEE*, B. Twala, *Senior Member*, *IEEE* and D. V. Nicolae, Member, *IEEE*

Abstract **– This paper deals with the effect of the combination of double and triple layer (DTL) winding configurations on axially laminated anisotropic (ALA) rotor synchronous reluctance motors. Three ALA rotor shapes are opted in this paper to evaluate the airgap flux density, torque average and torque ripple contents. The stator geometry of a 4-pole, 1.5 kW, conventional three-phase squirrel cage induction motor, having 36 slots is used. 2-D Finite Element Method (FEM) is utilized to analyse the performance of the machines. From the FEM results, it evidenced that DTL winding configuration reduced the airgap flux density Total Harmonic Distortion (THD), improved torque average and dropped the torque ripple contents in all three ALA rotor synchronous reluctance motors.**

Keywords— Average torque, Axially-laminated anisotropic rotor, Double-triple winding layout, Flux density, Synchronous reluctance motor, Torque ripple.

I. INTRODUCTION

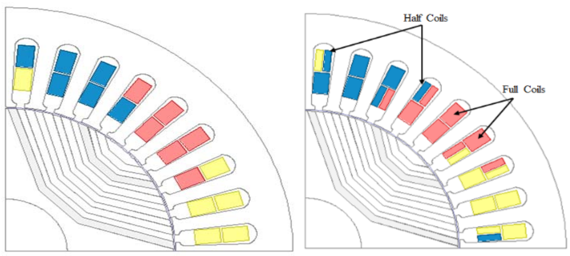
SYNCHRONOUS reluctance motors (SynRMs) are rugged, simple in structure, and cheaper to manufacture as compared with other types of AC machines [1]. Also, SynRMs have advantages such as high torque and efficiency than induction motors [2]. Therefore, they are advantageous to operate in traction motors or in high speed machines [2]. SynRMs with transverse-laminated anisotropic and ALA rotors have shown to have high saliency ratio [3], [4]. However, ALA type has a high torque per unit mass because there is no magnetic rib [2].

To date, efforts to optimize the design of ALA SynRMs have generally focused on one or two key rotor variables [4], [5]. For line-starting and inverter driven SynRMs, the stator winding is similar to the one used in induction machines. The stator is made of a laminated steel core with open or semi-closed uniformly distributed slots. The open slot configuration may be used to house multiphase concentrated single coils per pole per phase. As the airgap field open slot harmonics are important, significant torque pulsations occur, which may not be tolerable in some drives. Also, the Carter coefficient is high and reduces the direct-axis magnetizing inductance and thus a reduction in torque density is felt.

Semi-closed stator slots are used in this paper. The three-phase windings are made of distributed coils to produce a sinusoidal inductance-position curve rather than a linear dependence characteristic of concentrated coils. Effect of number of layers on performance of fractional-slot concentrated windings (FSCW) interior permanent magnet machines has been reported in [6], and the difference between single- and double layer FSCW in case of surface permanent magnet machine has been intensively investigated in literature [7], [8] and [9]. The impact of mixed winding configurations on torque ripple in multi-phase induction machines has been presented in [10].

In this paper, the effect of the conventional double layer (DL) and the combination of double and triple layers (DTL) on the performance of ALA SynRMs is analyzed. The DTL winding configuration and its design characteristics have well been reported in [10] and [11].

Fig. 1 depicts the cross-section of an ALA-type SynRM showing the distributions of coils per pole in DL and DTL winding configurations. Elsewhere in Fig.2, the complete coils of phase B for the DTL winding configurations are shown [11]. For a three-phase, 4-pole motor with 36 stator slots, the number of slots per pole per phase $q = 3$.



(a) (b)

Fig.1. Cross-section of an ALA-Type, (a) DL winding (b) DTL winding

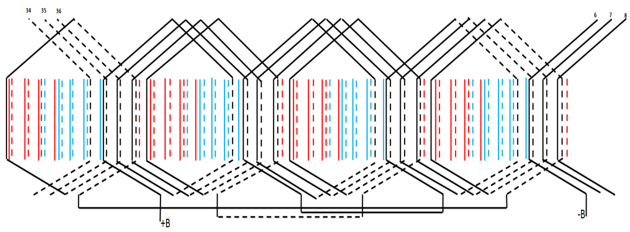


Fig.2. Double-triple winding layout, only coils for phase B are shown.

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The DTL winding configuration has in some slots conductors belonging to two different phases where one phase is made of a half coil and the other phase is made of one and a half coil. The currents in these phases are out of phase with one another by either $2\pi/3$ electrical radians or $4\pi/3$ electrical radians [11]. Consequently, the net currents and leakage flux are less than in the slots with the current belonging to the same phase. It should be noted that the phase band of the DTL configuration consists now of four slots, not three slots as in the conventional double layer winding [11]. Therefore, the phase-band angle of the DTL winding is $4\pi/9$ electrical radians, not $\pi/4$ like in conventional DL winding.

Furthermore, it is noted that the four slots of the phase-belt spread accommodate conductors that carry currents belonging to all the three phases.

II. Synchronous Reluctance Motors Specifications

Fig. 3 shows the three different rotor shapes of ALA SynRMs that are used in this paper [2], and table I illustrates the specifications pertain to the ALA SynRMs.

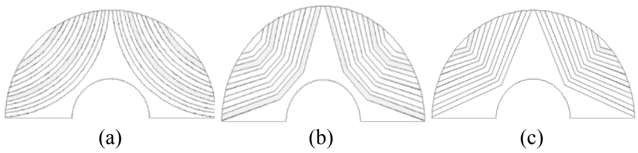

Fig.3: Various shapes of ALA SynRMs (a) ALA-type A, (b) ALA-type B, (c) ALA-Type C

TABLE I
SPECIFICATIONS OF THE MOTOR

Description	Value	Unit
Number of stator slots	36	-
Number of pole pairs	2	-
Number of phases	3	-
Number of turns per phase	216	mm
Stator outer diameter	135.00	mm
Stator inner diameter	80.00	mm
Rotor outer diameter	79.10	mm
Rotor inner diameter	29.00	mm
Lamination axial length	112.00	mm
Airgap length	0.45	mm
Thickness of insulation sheet	1.50	mm
Thickness of rotor lamination layer	2.00	mm
Number of axial lamination layers	6	-
Pole holder radial length	2.50	mm

III. Finite Element Model Results

A. Magnetic flux distribution and its Harmonic Contents

In this paper, a two-dimensional Finite Element Analysis (FEA) is performed using ANSYS 16.0 electromagnetic package. The FEA is carried out at constant speed and frequency of 1500-rpm and 50-Hz respectively. Both DL and DTL winding configurations are chorded by one slot.

Fig.4 (a) and (b), to fig. 6 (a) and (b), show the magnetic field lines obtained at initial rotor angular position of 17.5º. Elsewhere in Fig. 4 (c) and (d), to Fig.6 (b) and (d), the radial airgap flux density and its harmonic contents are illustrated. The stator windings are excited with pure sinusoidal currents. Then the airgap flux densities are plotted as a function of rotor position and decomposed into Fourier series.

It is observed from the FEA results that the effects of slot opening and rotor anisotopy are very visible in all ALA-types and contribute tromendousely to high space harmonic contents. By employing the DTL, the first belt harmonics (5^{th}) have been reduced by ± 3% in all ALA-types. Table II illustratates the comparison of the average airgap radial flux densities and their THDs. The pitch angle of the axial lamination layers between two adjacent poles is greater in ALA-types B and C. As consequence, the 9^{th} space harmonics are high in both ALA-types for any given winding configuration.

Despite high magnitude of 9^{th} space harmonics, It is observed that the DTL winding configuration has dropped the magnitude of the 9^{th} space harmonics by ± 5.5 % in both ALA-types B and C. The 9^{th} space harmonic can still be minimised by adopting a good design optimization of the ALA rotor shape.

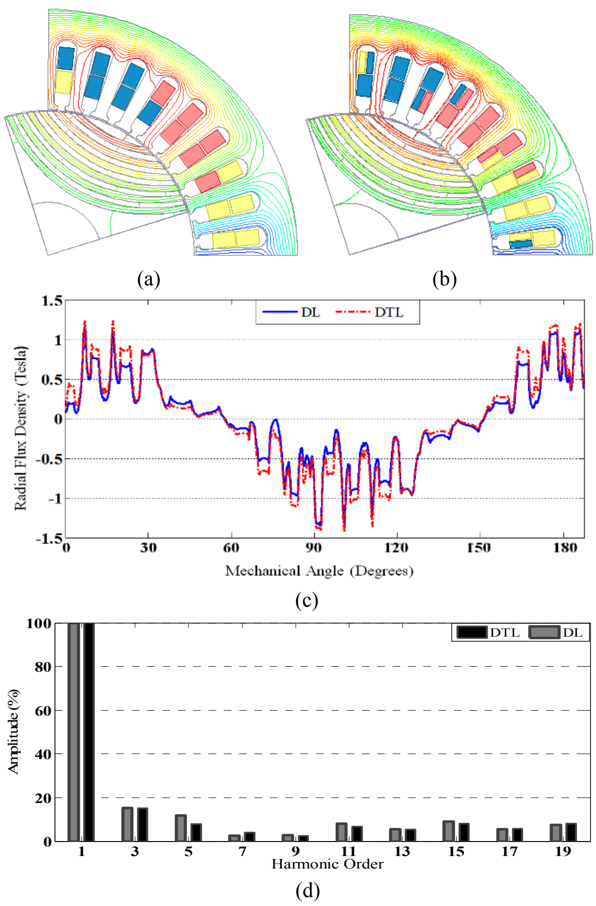

Fig. 4. Comparison between DL & DTL for ALA-type A, (a) Field lines for DL, (b) Field lines for DTL, (c) Airgap flux density, (d) FFT

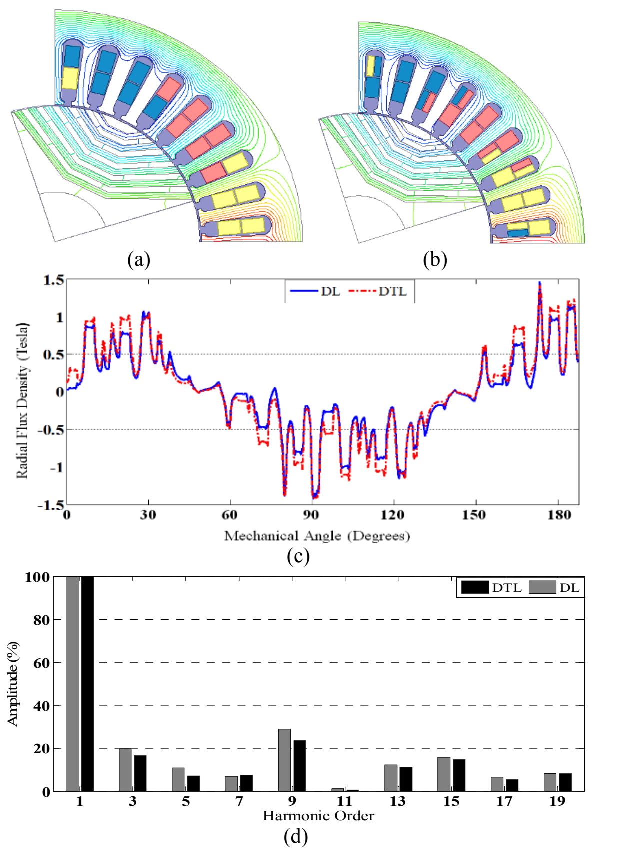

Fig. 5. Comparison between DL & DTL for ALA-type B, (a) Field lines for DL, (b) Field lines for DTL, (c) Airgap flux density, (d) FFT

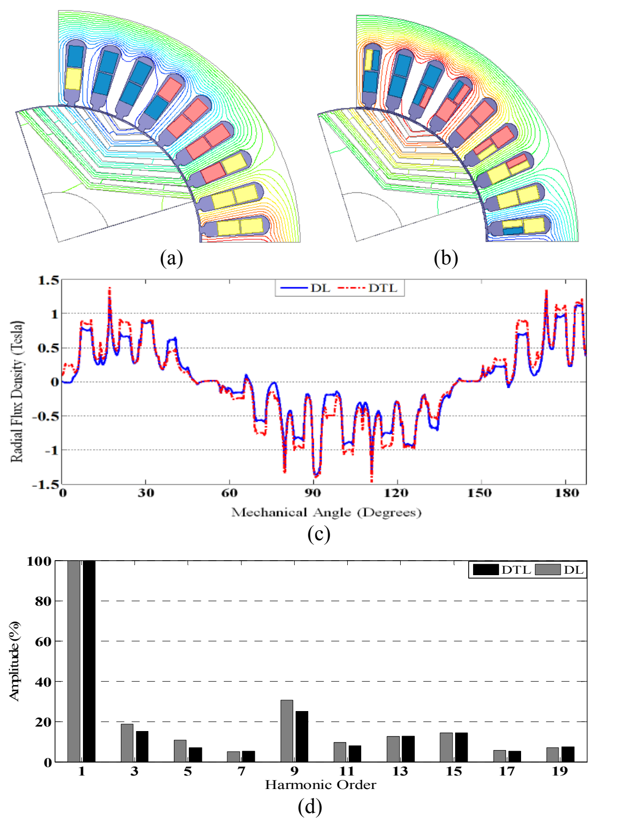

Fig. 6. Comparison between DL & DTL for ALA-type C, (a) Field lines for DL, (b) Field lines for DTL, (c) Airgap flux density, (d) FFT

In addition to the advantage that the DTL has over the DL winding configuration, the reduction in thickness of the axially laminated sheets can be employed. This would increase the number of sheets in the rotor but also increase the saliency ratio. Hence, the torque and flux-linkage can significantly increase with lower torque ripples. The harmonic distortion (THD) of the airgap flux density for DL and DTL employed to all three ALA-types, is caclulated by

$$THD = \frac{\sqrt{B_3^2 + B_5^2 + B_7^2 + \ldots}}{B_1} \quad (1)$$

TABLE II
RADIAL AIRGAP FLUX DENSITY AND ITS THD

Rotor Shape	DL		DTL	
	B_{av} (Tesla)	*THD* (%)	B_{av} (Tesla)	*THD* (%)
ALA-Type A	0.679	25.57	0.785	23.43
ALA-Type B	0.662	43.48	0.769	36.90
ALA-Type C	0.651	44.27	0.751	38.03

From table II, it is noticed that the ALA-types B and C have higth THDs and low average flux densities in both DL and DTL winding configurations. The reduction in magnetic properties in both ALA-Types B and C, is due to the shap bend of the lamination sheets.

In this paper, grain oriented steel sheets were used in the design of all three ALA rotor shapes. This material looses partly its magnetic properties whent it is bent and machined [14]. To restore in practice its original magnetic properties the material should be heat treated [14].

B. Effect of DTL winding configuration on Flux Linkage

The stator flux linkages of each of three-phase stator windings for these unskewed motors, neglecting the end-winding linkages, are calculated from the weighted average vector potentials by means of FEM and given by

$$\lambda = Nl(A_{avg+} - A_{avg-}) \quad (2)$$

Where N is the total number turns in the phase winding, l the effective winding length in the z direction, A_{avg+} and A_{avg-} being the average vector potential of the enter and return winding sides respectively.

Fig.7 shows the phase flux linkages of both winding configurations for the different ALA-types. As mentionend in pior section that the three-phase winding are made of distributed coils to produce a sinusoidal inductance-position curve. Therefore, all the flux linkage waveforms are nearly an exact sinusoidal due to the sinusoidal excitation current.

In ALA-type A, the flux linkage waveform of the DL winding lags slightly behind the flux linkage waveform of the DTL winding configuration. The expansion of the phase spread angle from $2\pi/3$ electric radian in conventional DL, to $4\pi/9$ electric radian in the DTL explains the shift in flux linkage position in ALA-type A. The effect is different in ALA-types B and C due to greater pitch angle of the axial lamination layers between two adjacent poles.

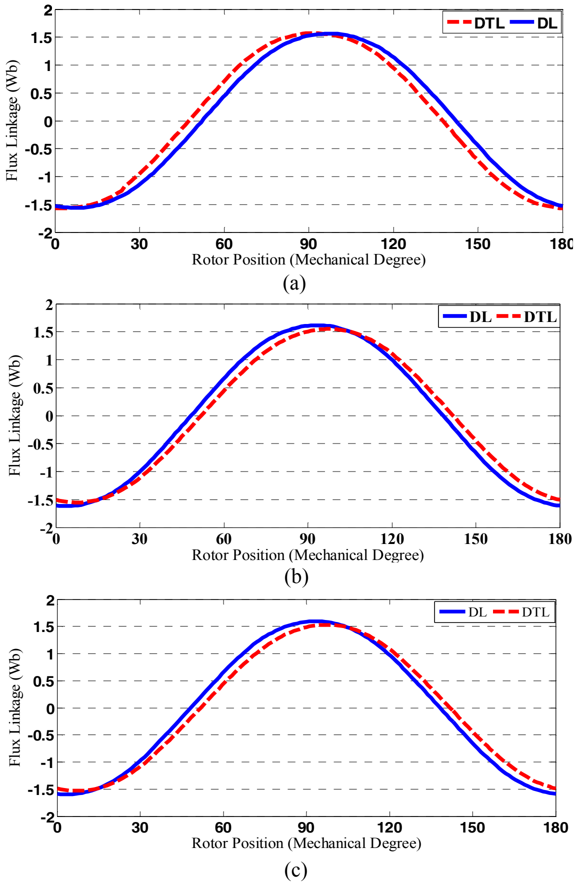

Fig. 7. Flux Linkage (a) ALA Type A, (b) ALA Type B, (c) ALA Type C

C. Effect of DTL winding configuration on back EMFs

The phase back EMFs of DL and DTL winding configurations employed to all three ALA-types are shown in Fig. 8 (a) to Fig. 10 (a). In order to evaluate the discret components of the back EMFs profiles, FFT was peformed. The FFT results are shown in Fig. 8 (b) to Fig. 10 (b).

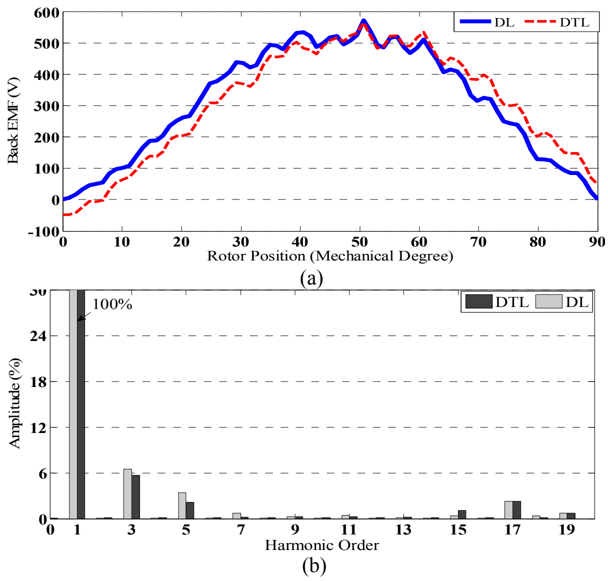

Fig. 8. Comparison of Phase back EMFs for ALA Type A
(a) Back EMF profiles, (b) FFT analysis

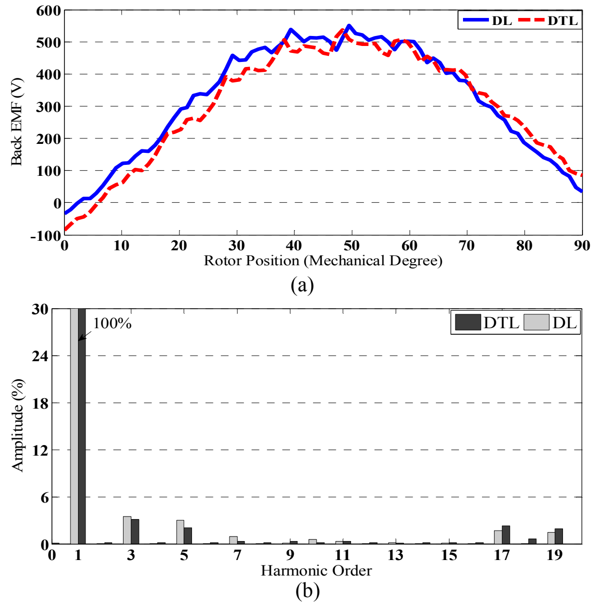

Fig. 9. Comparison of Phase back EMFs for ALA Type B
(a) Back EMF profiles, (b) FFT analysis.

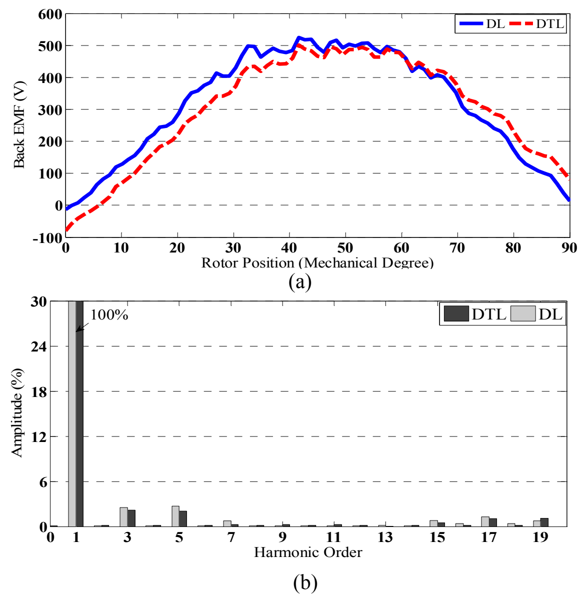

Fig. 10. Comparison of Phase back EMFs for ALA Type C
(a) Back EMF profiles, (b) FFT analysis

It is noted that the first phase-belt (5^{th}) back EMFs harmonics have been reduced in all three ALA-Types while employing the DTL winding configuration. The DTL winding reduced the amplitude of the 5^{th} back EMF harmonics from 3.4% down to 2.15 % in ALA-type A, from 3.03 % down to 2.06 % in ALA-type B, and from 2.67 down to 2.05 % in ALA-type C. The chording of the stator winding by one slot pitch has contributed to the lowering of the second phase belt (7^{th}) back EMFs harmonics in all three ALA-types. It also observed that the DTL configurations have very less 7^{th} bach EMFs harmonics as compared to DL winding configurations. Elsewhere, the 17^{th} and 19^{th} back EMFs harmonics are visible in all three ALA-types. These harmonics are dues to stator sloting and Cater effects.

D. Effect of DTL winding configuration on average torque and torque ripple

The machines were run at constant current space phasor angles of 45°electrical so that the *d*- and *q-axis* currents are the same in order to obtain maximum torque. The developed torque for the smooth air-gap SynRM is given as [12]:

$$T(\theta)=\frac{3}{2}\frac{p}{2}(L_d-L_q)i_d i_q=\frac{3}{2}\frac{p}{2}\left(L_d-L_q\right)I_s^2\sin\vartheta \qquad (3)$$

Where p is number of poles, L_d and L_q are the *d*-and *q*-axis inductances, I_s is the stator current space phasor, i_d and i_q are the *d*-and *q*-axis currents and ϑ is current space phasor angle. The torque profiles as function of position are shown in Fig. 11. The average torque and torque ripple contents are well depicted in table III.

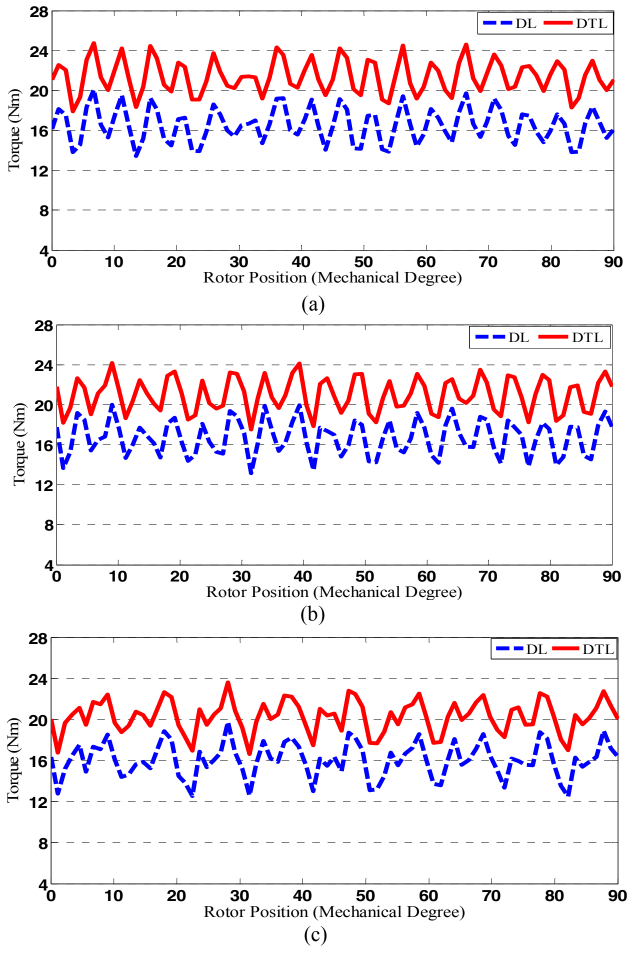

Fig.11. Instantaneous torque as function of rotor position at ϑ=45°, (a) ALA-Type A, (b) ALA-Type B, (c) ALA-Type C

The torque ripple factor defined as the ratio of peak to peak torque value to average torque is adopted for torque ripple calculation [13], which is expressed as

$$T_{ripple}=\frac{\Delta T}{T_{av}}\times 100=\frac{T_{\max}-T_{\min}}{T_{av}}\times 100 \qquad (4)$$

TABLE III
TORQUE COMPARISON

Rotor Shape	DL		DTL	
	$T_{av}(Nm)$	$\Delta T/T_{av}\,(\%)$	$T_{av}(Nm)$	$\Delta T/T_{av}\,(\%)$
ALA-Type A	16.52	40.10	21.39	32.01
ALA-Type B	16.70	40.92	20.98	31.86
ALA-Type C	16.04	45.37	20.27	34.67

Observing from table III, it is clear that the average torque in all ALA-types is approximately the same for each winding configuration. It is also evidenced from results that the DTL improves the average torque by ± 29.47 %, ± 25.63 % and ± 26.37 % for ALA-Type A, -Type B and -Type C respectively. It is also noticed that the DTL winding has reduced the torque ripple factor by 8.10 %, 9.06 % and 10.70 % for ALA-Type A, -Type B and -Type C respectively.

IV. CONCLUSION

This paper described the effect of DTL winding configuration in axially-laminated synchronous reluctance machines. The FEM results have shown that the DTL have improved the torque average by over 25 %, and reduced the torque ripple factor by over 8 % in all three types of ALA rotor shapes. The benefits of the DTL winding configurations can be added to the benefits of a good optimized rotor design, to largely mitigate the torque ripple contents in ALA SynRMs.

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VI. Biographies

Mbika Muteba received the Associate Degree of applied science and technology in electrical engineering from higher institute of technology (ISTC), Katanga, DRC, in 1996. After ten years of industrial experience in electrical machines, machines drives, primary and secondary power distribution networks both in DRC and South Africa, he joined the Tshwane University of Technology, South Africa, in 2006. He received the Bachelor's and Master's degrees of Technology in Electrical Engineering in 2008 and 2013, respectively. He is at his final phase of completing his PhD in Electrical and Electronic Engineering at the University of Johannesburg.

Muteba is imployed on permanent basis as a lecturer in the Department of Electrical and Electronic Engineering Technology at the University of Johannesburg. His research interests are design and control of electrical machines for future Electric and Hybrid Electric Vehicles.

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His research work involved an expanded swath of data, analytics, and optimization approaches that brings a more complete understanding of digital customer experiences. Prof Twala's current work involves promoting and conducting research in artificial intelligence within the electrical and electronic engineering science fields and developing novel and innovative solutions to key research problems in these areas.

He earned his Bachelor's degree in Economics and Statistics from the University of Swaziland in 1993; followed by an MSc in Computational Statistics from Southampton University (UK) in 1995; and then a PhD in Machine Learning and Statistical Science from the Open University (UK) in 2005. Prof. Twala was a post-doctoral researcher at Brunel University in the UK, mainly focussing on empirical software engineering research and looking at data quality issues in software engineering. His broad research interests include multivariate statistics, classification methods, knowledge discovery and reasoning with uncertainty, sensor data fusion and inference, and the interface between statistics and computing. He has particular interests in applications in finance, medicine, psychology, software engineering and most recently in robotics and has published over 70 scientific papers.

Prof. Twala has a wide ranging work experience to organisations ranging from banks, through universities, to governments. He is currently an associate editor of the Intelligent Data Analysis Journal, Journal of Computers, International Journal of Advanced Information Science and Technology, International Journal of Big Data Intelligence, Journal of Image and Data Fusion, Journal of Information Processing Systems, and a fellow of the Royal Statistical Society. Other professional memberships include the Association of Computing Machinery (ACM); the Chartered Institute of Logistics and Transport (CIT), South Africa and a senior member of the Institute of Electrical and Electronics Engineers (IEEE).

Dan Valentin Nicolae, born in Romania 18/09/1948, has got his first degree Master in (Applied) Electronic Engineering in 1971 from University Polytechnic of Bucharest, Romania. Between 1971 and 1975 he was with Institute for Nuclear Technologies as design engineer, than in 1975 he joined National Institute for Scientific and Technical Creativity – Avionics Branch in Bucharest Romania as principal researcher.

In 1998, D. V. Nicolae joined Tshwane University of Technology as lecturer for heavy current subjects. In 2000 he started his research activity in TUT with a stage in France; with this opportunity he started his PhD which has been finalized in 2004. In 2015 he joined University of Johannesburg. Presently, Prof. DV Nicolae is involved in research in power converters for power systems, electric machines, power systems and renewable energy.