Multi Layer Planar Concentrated Windings

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***Abstract*—Planar non-overlapping concentrated windings are simple to wind and robust in operation. Since the coils may be preformed before stator construction they yield a high slot packing factor. However all the forms of the windings produce backward going fields, which can detract from their performance when used in induction machines. A novel system has recently been developed to cancel the backward going fields and produce good performance from these simple windings. Starting with this system the paper develops a number of single-sided machines using multi layered planar coils and analyzes their performance. Machines using these windings are apt for higher voltages and are efficient to construct, with savings in both labor and material costs. The winding layouts for various forms of multi layer planar machine have been outlined and the good performance of these machines has been established compared to conventional two layer windings by both 3D finite element analysis and experimental methods.**

Keywords-Linear Machines; Linear Induction Motors; Concentrated Windings

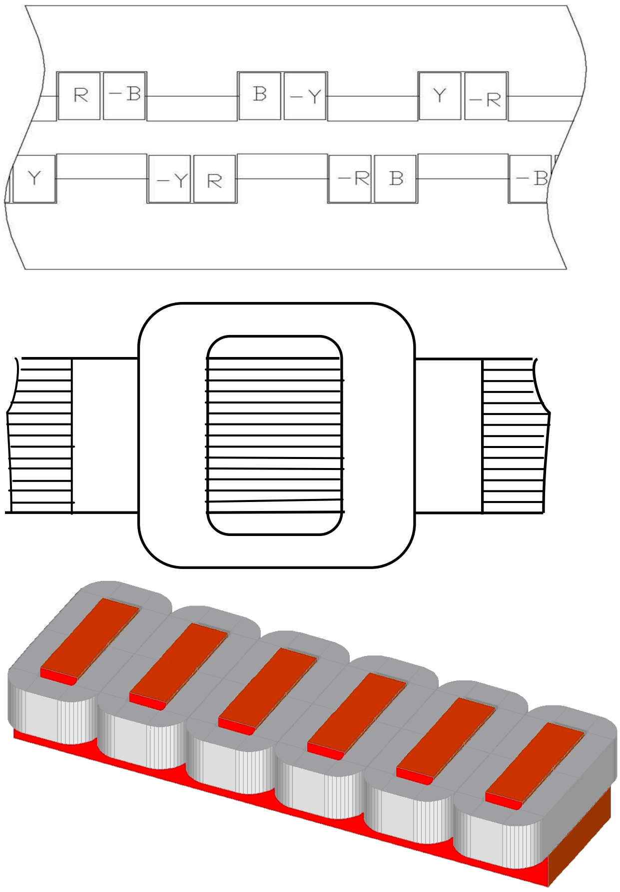
I. INTRODUCTION

Planar concentrated windings are apt for high voltage machines and permanent magnet motors. These simple and robust windings have been applied to double-sided induction machines, where two stators on either side of a conductive sheet are offset to cancel unwanted mmf harmonics. The use of planar concentrated windings in induction motors gives significant advantages due to simplified production, reduced material requirements and improved reliability when compared to traditional double layer type windings.

A method has been developed to use layered planar concentrated windings with a single sided configuration to successfully cancel unwanted harmonics. This removes the need for a double sided configuration and improves the magnetic gap. 2D and 3D Finite Element Analysis and a prototype confirm the excellent performance of this configuration.

II. CONCEPT

The offset stator configuration shown in Fig. 1 is a simple, inexpensive and robust form of stator winding. This winding type has been shown to give good performance from a conductive rotor by use of a mechanical offset to cancel unwanted mmf harmonics in the airgap [1][2].



a

b

c

Figure 1. Offset concentrated winding

a. Side view

b. Plan view of a coil

c. 3D Image of a stator

The prime limitation of this configuration is that the need for a physical offset requires the use of two stators on opposite sides of the airgap, known as a double-sided configuration. While this is a common configuration for linear induction machines, it is advantageous in some applications to work with a single stator and rotor in a single-sided configuration. A single-sided version of the offset winding which still cancels unwanted harmonics has been developed, the simplest form of which is shown in Fig. 2.

The new configuration contains two planar layers of coils, with twice the number of slots and half the slot pitch of the offset machine. Harmonic analysis of the single layer 6 coil 4/8 pole winding Fig. 3 when compared with that from the two layer planar configuration Fig. 4 suggests that the large 8 pole winding factor harmonic present in a single layer 6 coil 4/8 pole winding [3] has been completely eliminated. Fig. 5 shows the airgap flux of a two layer planar winding using FEA, and shows that the airgap flux B_y produced by this winding contains only the fundamental 4 pole and a minor 20 pole harmonic.

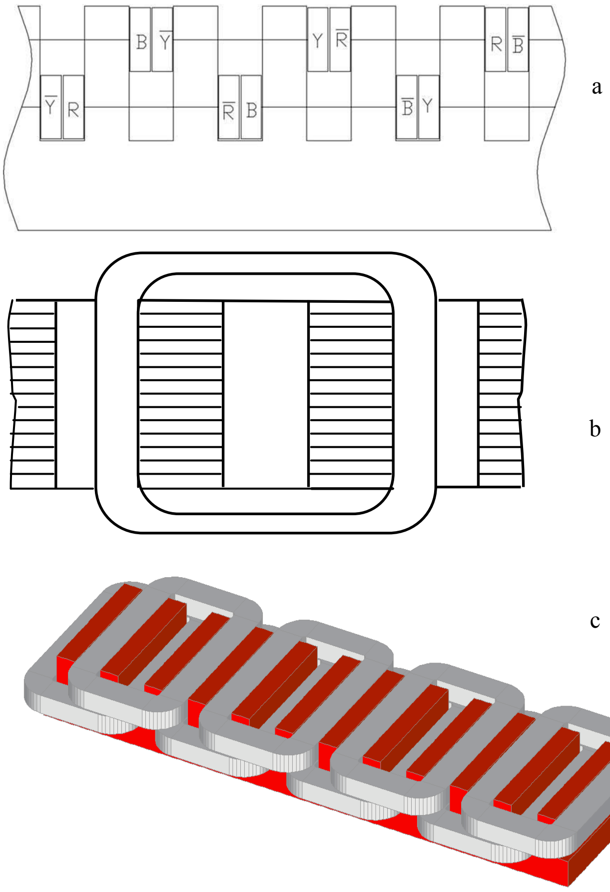


Figure 2. Two layer planar concentrated winding

a. Side view

b. Plan view of a coil

c. 3D Image of a stator

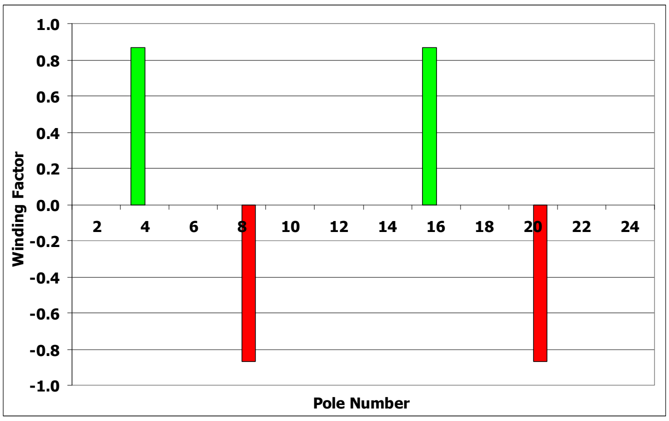


Figure 3. Single layer planar winding calculated harmonic spectrum

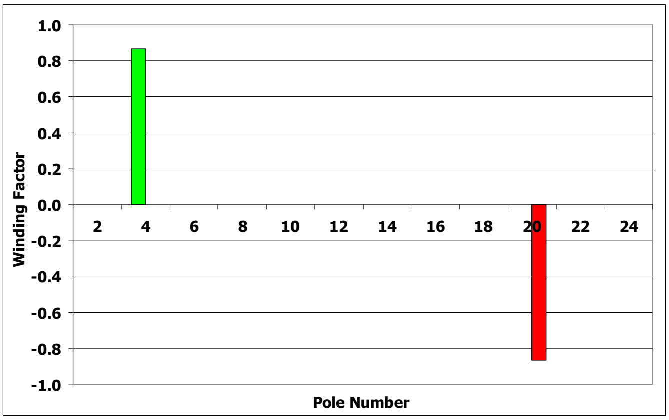


Figure 4. Two layer planar winding calculated harmonic spectrum

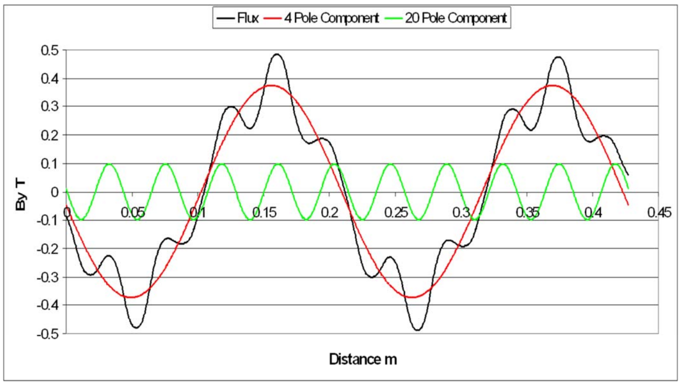


Figure 5. FEA modelled airgap flux for two layer planar winding showing principal harmonic components

An obvious disadvantage of this method is that the effective slot fill of the machine is reduced by half, due to the use of only the top or bottom half of alternate slots.

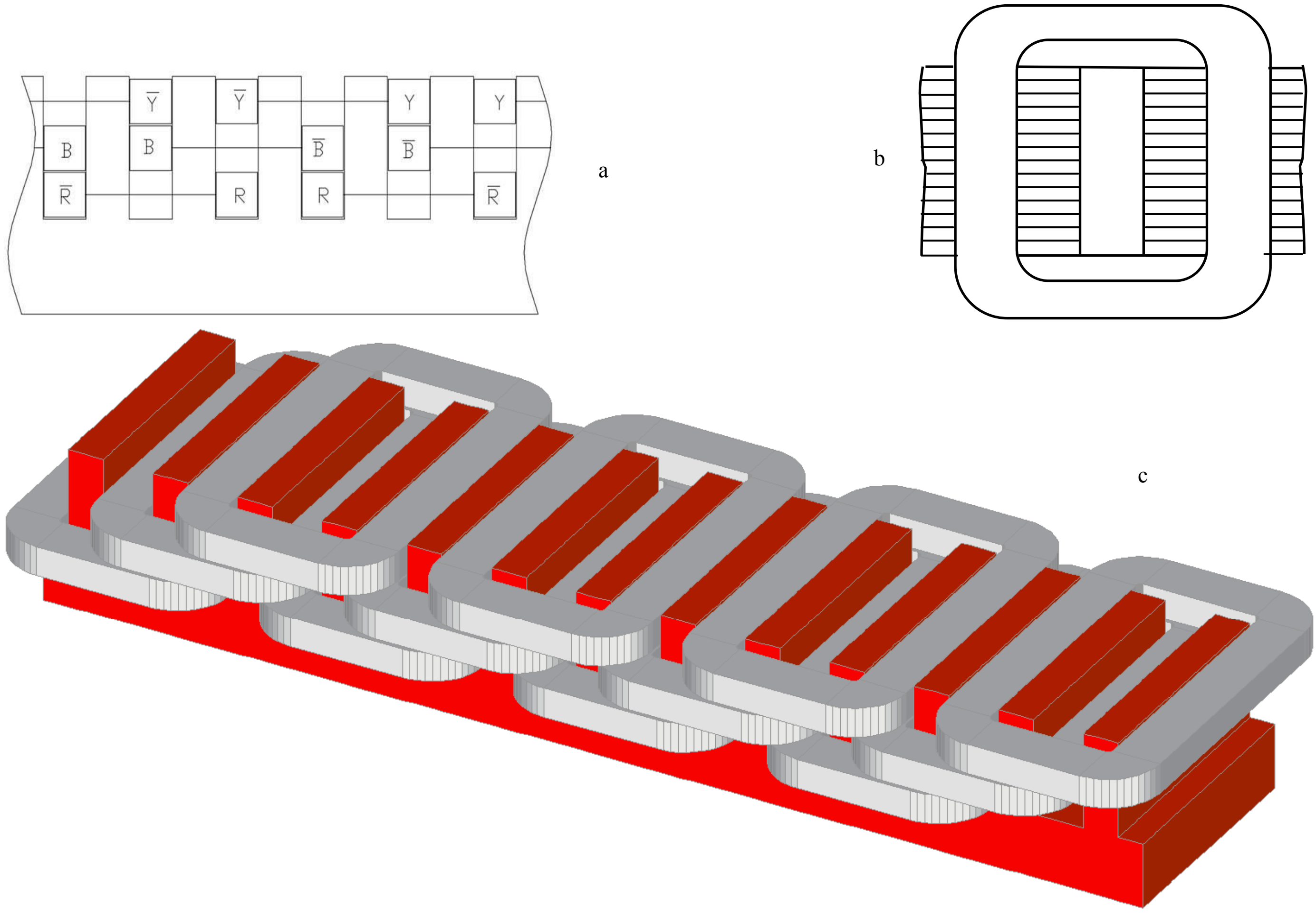


Figure 6. Three layer planar concentrated winding

a. Side view b. Plan view of a coil c. 3D Image of a stator

An alternative method which increases the machine slot fill and is simpler electrically consists of separating the machine coils further into three distinct layers as in Fig. 6. This technique raises the basic slot fill to 2/3 and has the potentially significant advantage that for a 3 phase machine, each layer of coils fed from one phase, allowing for very simple and effective inter-phase electrical insulation and so making the machines advantageous for use in high voltage applications. A technique resulting similarly in three single phase layers was used for a pole change winding [4] and an airgap winding [5].

If concentric coils are employed, the machine slot fill can be improved still further. Fig. 7 & Fig. 8 show a continuous form of a 3 layer planar winding using 4 pairs of 2 concentric coils per phase. This configuration gives 100% slot fill and reduces stator end turn leakage reactance [6] but also introduces a distribution factor which reduces the overall winding factor of the machine.

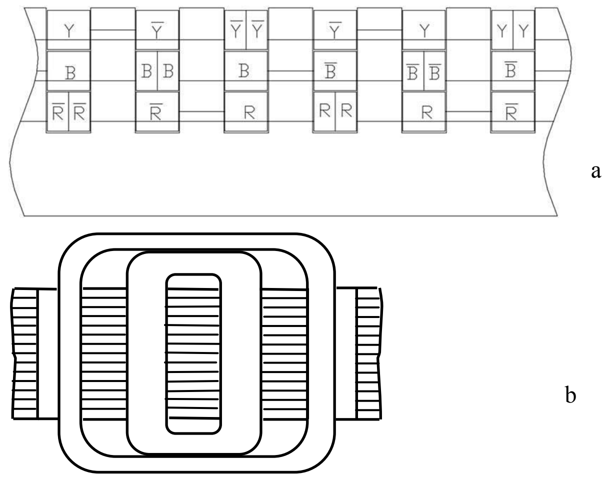


Figure 7. Three layer planar 2 coil concentric winding

a. Side view

b. Plan view of a coil

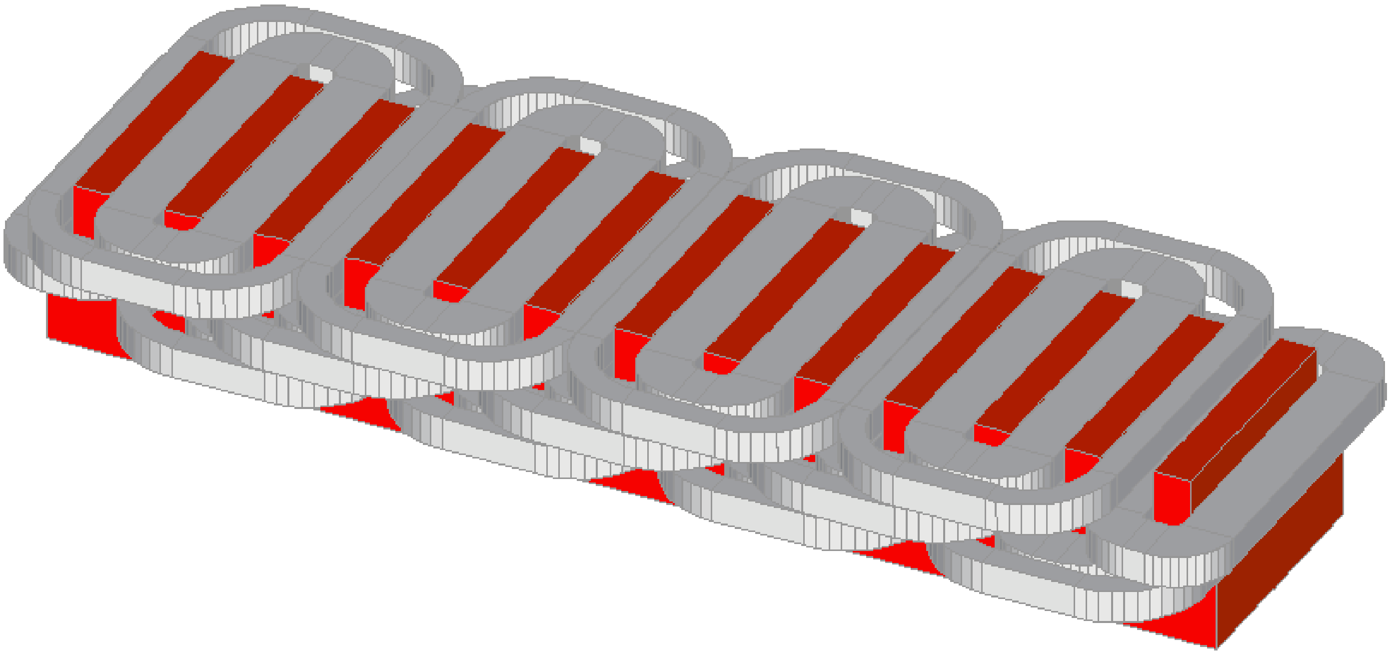


Figure 8. 3D Concentric coil 3 layer stator model

III. Modeling and Results

The three layer planar coil machine designs were compared to a 2 layer mush wound stator of similar dimensions. A comparison of the basic physical characteristics of the two machines is shown in Table 1. The three layer planar coil machine designs were initially verified by modeling using 2D Finite Element Analysis using the MEGA FEA package. The results of this comparison can be seen in Fig. 8. It can be seen that the thrust produced from the three layer planar winding is close to but slightly lower and the current draw slightly higher than the comparative machine, indicating a small tradeoff in performance in return for improved physical and cost characteristics.

TABLE I. Three layer linear machine comparative dimensions and costs

	Three Layer Planar	**Two layer mush wound**
Length	104%	100%
Width	70%	100%
Weight	90%	100%
Number of Coils	12	24
Estimated Production Cost	75%	100%

A prototype of the three layer planar coil machine was then produced in order to confirm the performance of three layer machines in comparison with a separate two layer winding machine of similar dimensions. The stall results from this testing are shown in Table 2.

From Table 2 it can be seen that force, current and power factor for the experimental machine are all close to the values predicted by 3D FEA.

TABLE II. Three layer linear machine stall results

	Force N	**Current A**	**Cos Phi**
Three layer - 3D FEA	434	25.0	0.64
Three layer - Experimental	401	22.9	0.66
Conventional two layer linear machine	386	19.3	0.53

It can further be seen that output force in this configuration is again similar to that from a comparable mush wound two layer 5/6ths chorded linear machine. The three layer machine draws slightly more current but has a significantly improved power factor. A further significant benefit is that the three layer machine is 75% of the machine width of the comparable machine for the same length, depth and core width. The reduced end turns also use less material in construction The simple layered coil system makes the three layer machine faster and easier to build and apt for high voltage applications.

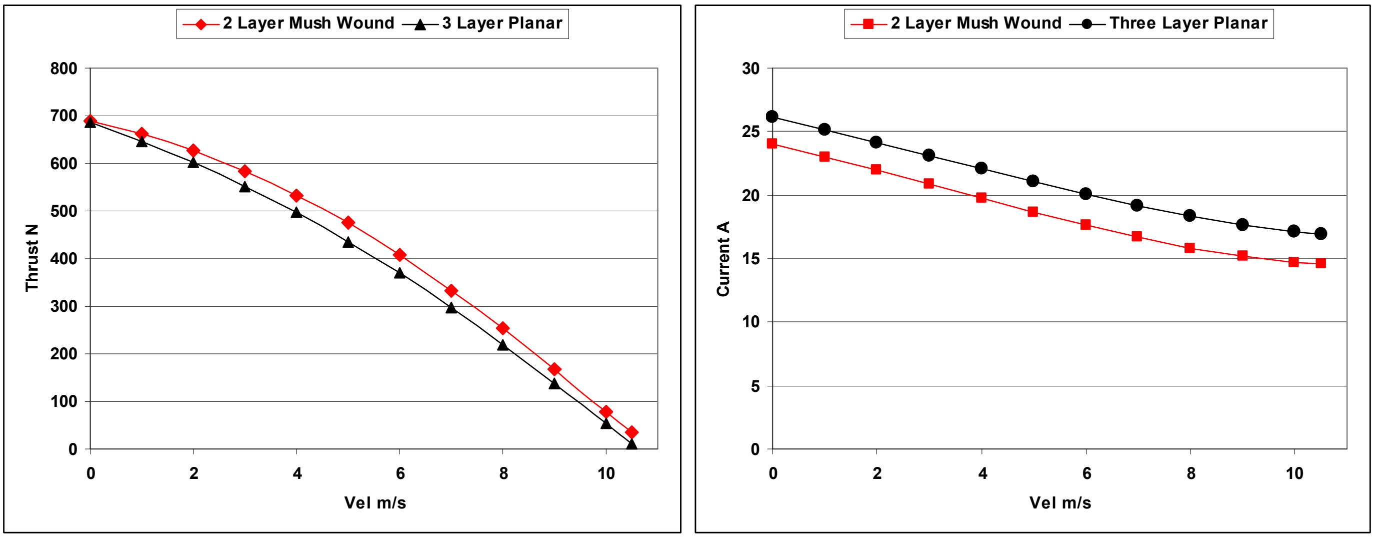


Figure 9. Thrust and Current draw for a three layer planar winding compared to two layer mush winding

IV. A Comparison of the Windings

The windings are all balanced and symmetrical and so the fundamental winding factors can be calculated from the usual spread and chording factor expressions.

The offset concentrated winding of Fig. 1, the two layer winding of Fig. 2 and the three layer planar winding of Fig. 6 all have one coil per phase group and a coil pitch of 2/3rds of a pole pitch. The fundamental winding factor for these windings is 0.866. The three layer planar 2 coil concentric winding of Fig. 7 has effectively 3 coils per phase group spaced by $\pi/3$ radians that are fully pitched. Its fundamental winding factor is 0.666. The effectiveness of the windings can be judged by the current loading (J_s) produced, this is given by INk/w where N is the number of conductors per slot, I the current per conductor, k the winding factor and w is the slot pitch. The factors for the various windings and the resulting current loadings are given in Table 3.

TABLE III. Factors and current loading produced by the windings

	Slot conductors	Slot pitch	k	Js (w/IN)
One side of the offset winding	N	w	0.866	0.866
Two layer planar concentrated	N/4	w/2	0.866	0.433
Three layer planar	2N/3	w/2	0.866	0.577
Three layer planar 2 coil concentric	N/2	w/2	0.666	0.666

It is assumed that a full slot for the offset winding contains N conductors and that the slot pitch is w. From the table it is apparent that the three layer concentric winding gives the best result amongst the non-offset windings. However it must be remembered that the winding is more costly to produce. None of the new windings produces as much current loading as the offset concentric per side. This is mitigated since the offset winding is reduced in effectiveness by the regions at each end of the system where the reaction plate is covered only on one side, due to the physical offset of the stators.

The very maximum effect that this could have depends on the ratio of the pole pitch to the machine length but for a 6 coil 4 pole machine wound as in Fig. 1 could approach a factor of 5/6 reducing the effective J_s to 0.722, compared with 0.666 from the three layer concentric.

The full harmonic winding factor analysis of the various winding configurations can be found in Appendix 1.

V. Conclusions

The multi layer planar concentrated winding proves to be an excellent configuration, allowing the use of single sided simple planar windings whilst removing the negative harmonic content which would otherwise be extremely detrimental to their use with induction machines. The use of the three layer windings is very apt for high voltage machines, as individual phases occupy distinct layers and so can be simply and effectively insulated from one another. The simple coils can be easily preformed before insertion in the slots yielding a high slot packing factor, however no account has been taken of this advantage for the work in this paper. The simple coils of the concentrated machines have minimal end turns, reducing material use and stator winding resistive losses. This is particularly beneficial when compared to machines using fully formed coils. The reduced end turns also resulted in a 3 layer machine with the same active area as a comparative two layer 5/6ths chorded winding, but only 75% of the width and volume. If the active area of the machine was increased whilst maintaining the same overall machine width, performance would be significantly improved on that of the comparative machine.

VI. REFERENCES

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VII. APPENDIX 1: WINDING ANALYSIS

A. General Case[7]

Phase 'a' of a general machine winding which consists of a group of coils connected in series gives a conductor distribution for the p_{th} harmonic of:

$$\overline{N}_{pa} = \frac{1}{\pi}\sum_{s=1}^{s=S} N_{sa}\varepsilon^{-jp\theta_{sa}} = N_{pa}\varepsilon^{-j\phi_{pa}} \quad (1)$$

Similarly for the 'b' and 'c' phases

$$\bar{N}_{pb} = N_{pb}\varepsilon^{j\phi_{pb}} \text{ and } \bar{N}_{pc} = N_{pc}\varepsilon^{j\phi_{pc}} \quad (2)$$

The winding distributions of a 3 phase winding may be represented by positive, negative and zero phase sequence sets each having three balanced windings. For a balance current input the zero sequence set can be ignored.

For balanced windings given by:

$$\bar{N}_{pa} = N_p, \quad \bar{N}_{pb} = N_p\varepsilon^{-2\pi p/3} \quad (3)$$

and

$$\bar{N}_{pc} = N_p\varepsilon^{2\pi p/3} \quad (4)$$

The positive sequence $n_{fp} = N_p$ if $p = 1,4,7...$ and is zero for all other values

The negative sequence $n_{np} = N_p$ if $p = 2,5,8.....$ and is zero for all other values

That is when the winding is fed with a balanced set of 3 phase currents, positive going waves are produced at p=1, 4, 7… and negative going waves are produced when p= 2, 5, 8…

B. Analysis of the Novel Windings

1) Two layer planar concentrated winding

This winding is shown at Fig. 2. Here from equation (1)

$$\overline{N}_{pa} = \frac{N_{sa}}{\pi}\{\varepsilon^{-jp0} - \varepsilon^{-jp2\pi/3} - \varepsilon^{-jp\pi} + \varepsilon^{-jp(\pi+2\pi/3)}\} \quad (5)$$

For p even

$$\overline{N}_{pa} = 0 \quad (6)$$

For p odd

$$\overline{N}_{pa} = \frac{2N_{sa}}{\pi}\{1 - \varepsilon^{jp2\pi/3}\} \quad (7)$$

$$\overline{N}_{pa} = \frac{4N_{sa}}{\pi}\varepsilon^{-jp\pi/3}\{\varepsilon^{jp\pi/3} - \varepsilon^{-jp\pi/3}\} \quad (8)$$

$$\overline{N}_{pa} = \frac{2N_{sa}}{\pi}j\varepsilon^{-jp\pi/3}\sin\frac{p\pi}{3} \quad (9)$$

The winding factor, k_w is defined as the modulus of the winding distribution divided by the maximum value it could have. This maximum value is $\frac{4N_{sa}}{\pi}$ so

$$k_w = \sin p\pi/3 \quad (10)$$

for $p = 1$ $k_{w1} = 0.867$

Positive winding sequences occur at p = 1,7..
Negative winding sequences occur at 5,11…

2) Three layer planar concentrated winding

Here the configuration of each phase shown in Fig. 6 is the same as in the above two layer planar winding and the harmonic winding factors are the same.

3) Three layer planar 2 coil concentric concentrated winding

This winding is shown at Fig.7. Using (1)

$$\overline{N}_{pa} = \frac{N_{sa}}{\pi}\{\varepsilon^{-jp(-\pi/3)} + \varepsilon^{-jp0} + \varepsilon^{-jp(\pi/3)} - \varepsilon^{-jp(\pi-\pi/3)} - \varepsilon^{-jp(\pi)} - \varepsilon^{-jp(\pi+\pi/3)}\} \quad (11)$$

For p even

$$\overline{N}_{pa} = 0 \quad (12)$$

For p odd

$$\overline{N}_{pa} = \frac{2N_{sa}}{\pi}\{1 + 2\cos(p\pi/3)\} \quad (13)$$

and

$$k_w = \{1 + 2\cos(p\pi/3)\}/3 \quad (14)$$

for $p = 1$ $k_{w1} = 0.667$