Effect of Number of Layers on Performance of Fractional-Slot Concentrated-Windings Interior Permanent Magnet Machines

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***Abstract*—Interior PM machines equipped with fractional-slot concentrated-windings are good candidates for high-speed traction applications. This is mainly due to the higher power density and efficiency that can be achieved. The main challenge with this type of machines is the high rotor losses at high speeds/frequencies. This paper will thoroughly investigate the effect of number of winding layers on the performance of this type of machines. It will be shown that by going to higher number of layers, there can be significant improvement in efficiency especially at high speeds mainly due to the reduction of the winding factor/magnitude of the most dominant stator mmf subharmonic component. It will also be shown that there is significant improvement in torque density. Even though there is reduction in the winding factor of the stator synchronous torque-producing mmf component, this is more than offset by increase in machine saliency and reluctance torque. The paper will provide general guidelines regarding the optimum slot/pole/phase combinations based on torque density and efficiency. Sample designs of various slot/pole combinations are used to quantify the benefit of going to higher number of layers in terms of torque density, efficiency, and torque ripple.**

***Index Terms*—Concentrated winding, fractional slot, interior permanent magnet, multiple winding layers.**

I. INTRODUCTION

INTERIOR PM (IPM) machines have been shown to be good candidates for high-speed traction applications. The use of fractional-slot concentrated-windings (FSCW) has shown that further improvement in terms of the machine end–end length as well as flux weakening ability can be achieved. Higher power density is achieved with higher speed ranges and higher efficiency are achieved with the flux weakening control algorithms [1]. However one of the main disadvantages with this type of machines is presence of high rotor losses. In a machine equipped with FSCW, high rotor losses are caused due to presence of both sub- and super-stator mmf components in the stator winding mmf.

In FSCW IPM machines, the torque-producing harmonic is a higher order harmonic, which is different from the first (or fundamental) harmonic component derived from the winding function. The fundamental harmonic component in most cases determines the subharmonic losses [2], which represents the majority of the high-speed losses especially on the rotor side. Usually there is a tradeoff involved in the selection of the optimum slot/pole combinations. In the configurations, where the winding factor of the torque-producing harmonic component is quite high, the power density is maximized. However if the winding factor of the fundamental or the first loss-producing harmonic component is high, the configuration also yields high subharmonic losses or in other words, has low efficiency.

The difference between single- and double-layer FSCW in the case of surface PM (SPM) machines has been extensively investigated in literature [3]–[6]. Recently there has been growing interest in higher number of winding layers (e.g., 3 and 4 layers) [7]–[9].

Nakano [10] looks at the sub- and super-harmonics identifying the suitable designs based on "rate of eddy current loss," which is itself based on the mmf of the other harmonics. Various designs belonging to slot/pole/phase (spp) combinations of 1, 1/2, 3/5, 3/4, and 4/5 are compared on this relative scale, with the final emphasis on 1 spp combination. Also study by Di Gerlando [11] regarding the multilayer windings in the application of electric traction has not been very conclusive. Kometani *et al* [12] consider the cases with the slot number being multiple of 9, i.e., number of slots being $9n$, where n is an integer, and the rotor having eight poles, effectively making a configuration of 3/8 spp.

Still the focus is mainly on SPM machines. In the case of SPM machines, there is usually a clear tradeoff involved in introducing of multiple winding layers. On one hand, higher number of layers is known to reduce the harmonic content in the winding function, making it more sinusoidal and hence reducing the additional harmonic losses. On the other hand, the winding factor of the torque-producing harmonic component is also reduced, leading to reduction in machine torque density. In case of FSCW-IPM machines the tradeoff is more interesting due to the presence of saliency. In this case, the reduction of loss-producing harmonics will have an effect on both the machine efficiency as well as torque density. This is due to the change in machine saliency (due to saturation effects) and hence reluctance torque contribution. This will be quantified in full details in the paper.

The paper will identify guidelines to choose optimum spp combinations for higher number of layers. Figures showing the one, two and four layer windings in machine belonging to the one of the spp family are shown in Figs. 1–3 respectively. Higher number of layers adds complexity in terms of the winding

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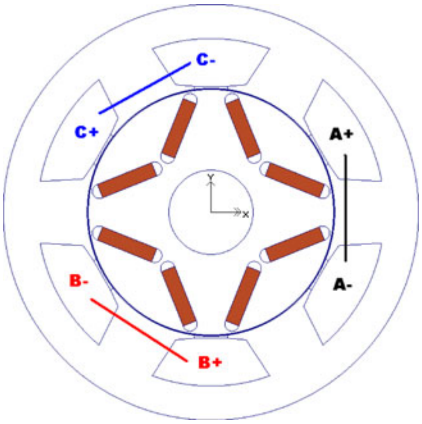


Fig. 1. Single layer winding.

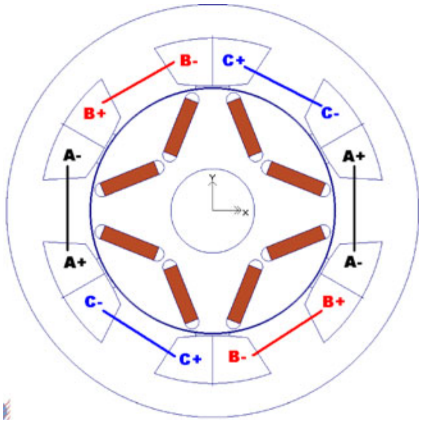


Fig. 2. Double (two) layer winding.

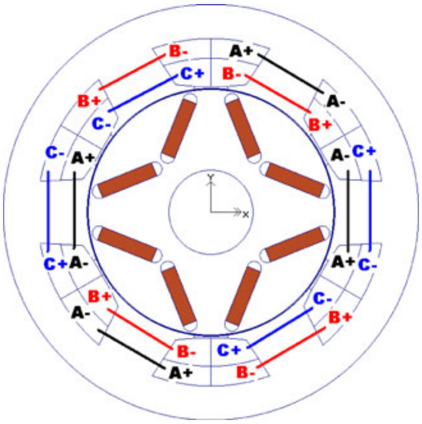


Fig. 3. Four layer winding.

pattern along with the manufacturing, while also increasing the number of coils/slot and has an effect of reduction in the slot fill factor due to increased area of insulation.

The benefits include high winding factors for the torque-producing harmonic component and low winding factors for the most dominant loss-producing harmonic components. The focus will be on four-layer winding configurations. The 12-slot/10-pole designs (belonging to the 2/5 spp family) are considered as an example as shown in Fig. 6. The effect of the number of layers on torque density, efficiency and torque ripple will be investigated. Similar effects of the number of layers on two other slot/pole combinations—3/7 and 3/8—are also discussed. Emphasis is laid on identification of an appropriate slot/pole combination for a hybrid traction application.

II. WINDING FACTORS TABLES

One of the key metrics in the understanding of the effect of the number of layers is winding factors. Since the fundamental component is not the torque-producing component in FSCW machines, the number of poles on the rotor side identifies the torque-producing component.

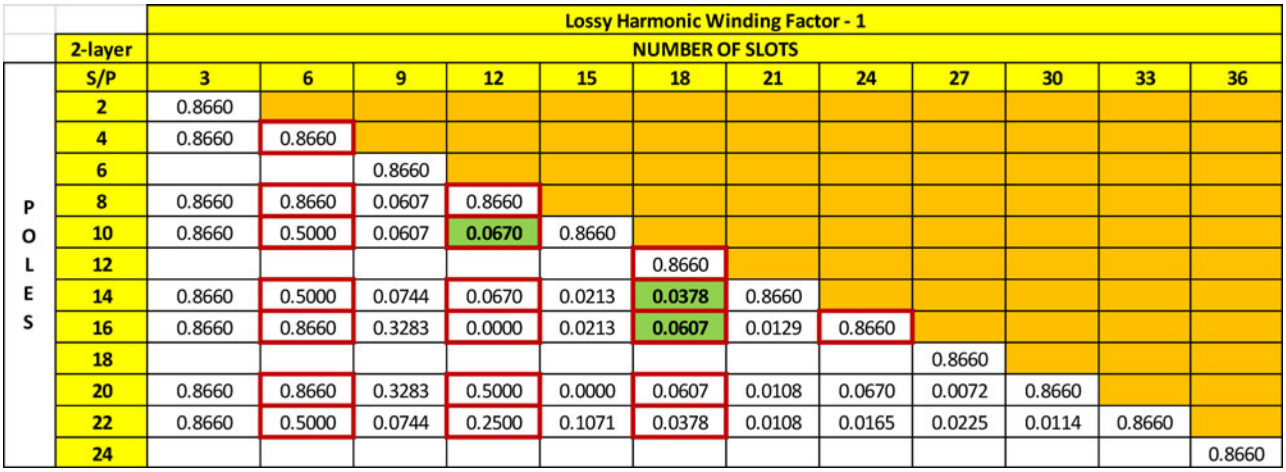
Since FSCW include a lot of sub- and super-harmonics as previously mentioned, a lot of attention has to be focused on the losses generated by these harmonic components. A good indicator of these losses, is the winding factor of the first (most-dominant) loss-producing harmonic component.

A. *Effect of Multilayer Windings on the Winding Factors*

The winding factors of the torque-producing components for the different slot/pole combinations are well documented in literature [5]. Tables I and II show the winding factors of the first and the second loss-producing harmonic components of various slot/pole combinations utilizing *two-layer* windings. Table III shows the synchronous (torque-producing) winding factor for different slot/pole combinations in case of four-layer windings. As expected, it can be seen that going from two to four layers, in general, the synchronous winding factor is reduced with some few exceptions lie. For example, for the 2/5th spp family, the torque-producing component is the 5th harmonic, whose winding factor reduces from 0.933 (double layer) to 0.901 (4-layer). It is expected that this reduction would reduce the machine torque density.

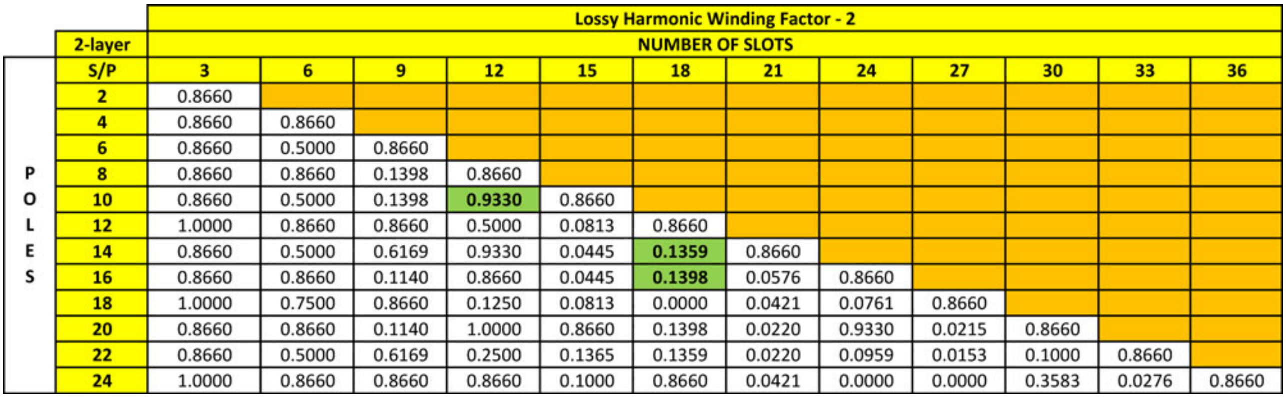
The main reason for the introduction of the multilayer windings is the improvement of efficiency. The main loss-producing harmonic for the FSCW configurations is usually the subharmonic components. For example, for the 2/5th spp configuration, while the 5th harmonic produces the torque, it is the fundamental component of the winding function, which produces the rotor losses. The magnitude of this loss-producing harmonic is important for the loss producing mechanism, with the winding factor being 0.0173 in the 2/5th spp configuration as shown in Table IV. Tables IV and V show the winding factors of the first and the second loss-producing harmonic components of various slot/pole combinations utilizing *four-layer* windings. Table VI shows the corresponding first two lossy harmonics for each slot/pole configuration. It is clear from Table IV that some configurations can be inherently very lossy, even though they can have high torque-producing winding factors. The ½ spp family is a good example of such configurations. The effect of the winding layers on the winding factors of the torque-producing and the loss-producing harmonics for the 2/5th spp is seen in Fig. 4. Although the highest winding factor of 0.966 is obtained in single layer windings, these windings also have a

TABLE I
WINDING FACTORS OF FIRST LOSS-PRODUCING COMPONENT FOR TWO-LAYER WINDING CONFIGURATIONS



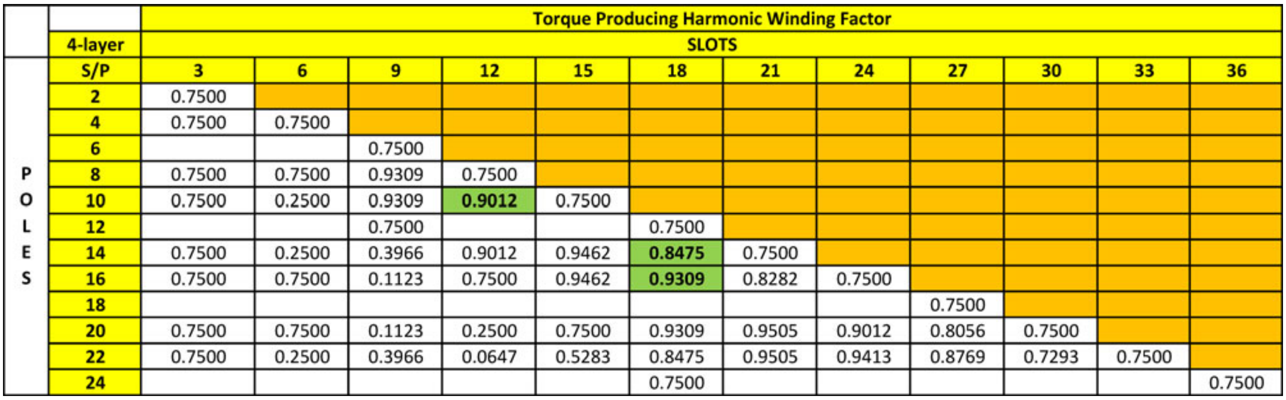
		Lossy Harmonic Winding Factor - 1											
	2-layer	NUMBER OF SLOTS											
	S/P	3	6	9	12	15	18	21	24	27	30	33	36
POLES	2	0.8660											
	4	0.8660	0.8660										
	6			0.8660									
	8	0.8660	0.8660	0.0607	0.8660								
	10	0.8660	0.5000	0.0607	**0.0670**	0.8660							
	12						0.8660						
	14	0.8660	0.5000	0.0744	0.0670	0.0213	**0.0378**	0.8660					
	16	0.8660	0.8660	0.3283	0.0000	0.0213	**0.0607**	0.0129	0.8660				
	18									0.8660			
	20	0.8660	0.8660	0.3283	0.5000	0.0000	0.0607	0.0108	0.0670	0.0072	0.8660		
	22	0.8660	0.5000	0.0744	0.2500	0.1071	0.0378	0.0108	0.0165	0.0225	0.0114	0.8660	
	24												0.8660

TABLE II
WINDING FACTORS OF SECOND LOSS-PRODUCING COMPONENT FOR TWO-LAYER WINDING CONFIGURATIONS



		Lossy Harmonic Winding Factor - 2											
	2-layer	NUMBER OF SLOTS											
	S/P	3	6	9	12	15	18	21	24	27	30	33	36
POLES	2	0.8660											
	4	0.8660	0.8660										
	6	0.8660	0.5000	0.8660									
	8	0.8660	0.8660	0.1398	0.8660								
	10	0.8660	0.5000	0.1398	**0.9330**	0.8660							
	12	1.0000	0.8660	0.8660	0.5000	0.0813	0.8660						
	14	0.8660	0.5000	0.6169	0.9330	0.0445	**0.1359**	0.8660					
	16	0.8660	0.8660	0.1140	0.8660	0.0445	**0.1398**	0.0576	0.8660				
	18	1.0000	0.7500	0.8660	0.1250	0.0813	0.0000	0.0421	0.0761	0.8660			
	20	0.8660	0.8660	0.1140	1.0000	0.8660	0.1398	0.0220	0.9330	0.0215	0.8660		
	22	0.8660	0.5000	0.6169	0.2500	0.1365	0.1359	0.0220	0.0959	0.0153	0.1000	0.8660	
	24	1.0000	0.8660	0.8660	0.8660	0.1000	0.8660	0.0421	0.0000	0.0000	0.3583	0.0276	0.8660

TABLE III
WINDING FACTORS OF TORQUE-PRODUCING COMPONENT FOR FOUR-LAYER WINDING CONFIGURATIONS

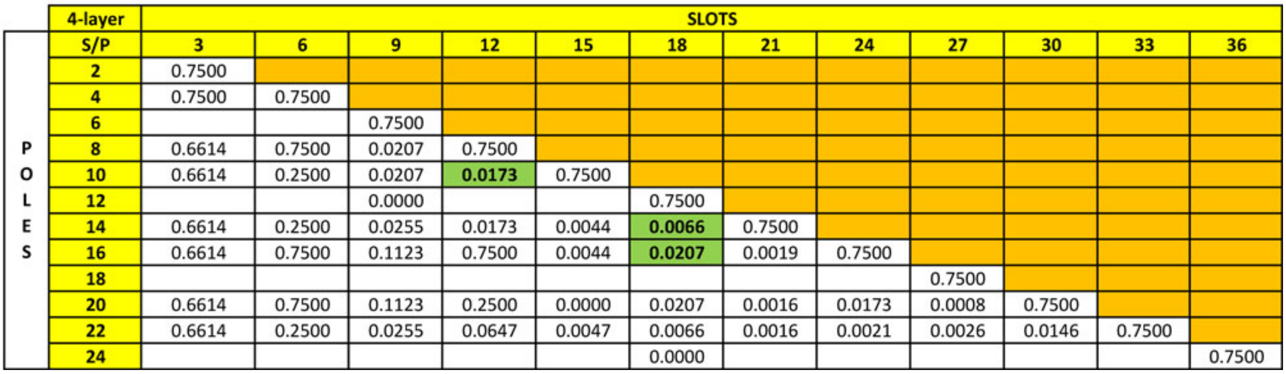


		Torque Producing Harmonic Winding Factor											
	4-layer	SLOTS											
	S/P	3	6	9	12	15	18	21	24	27	30	33	36
POLES	2	0.7500											
	4	0.7500	0.7500										
	6			0.7500									
	8	0.7500	0.7500	0.9309	0.7500								
	10	0.7500	0.2500	0.9309	**0.9012**	0.7500							
	12			0.7500			0.7500						
	14	0.7500	0.2500	0.3966	0.9012	0.9462	**0.8475**	0.7500					
	16	0.7500	0.7500	0.1123	0.7500	0.9462	**0.9309**	0.8282	0.7500				
	18									0.7500			
	20	0.7500	0.7500	0.1123	0.2500	0.7500	0.9309	0.9505	0.9012	0.8056	0.7500		
	22	0.7500	0.2500	0.3966	0.0647	0.5283	0.8475	0.9505	0.9413	0.8769	0.7293	0.7500	
	24						0.7500						0.7500

high winding factor for the loss-producing harmonic, reaching up to 0.259. Increasing the number of layers up to four reduces the winding factor of the loss-producing harmonic, while also reducing the winding factor of the torque-producing component in the machine.

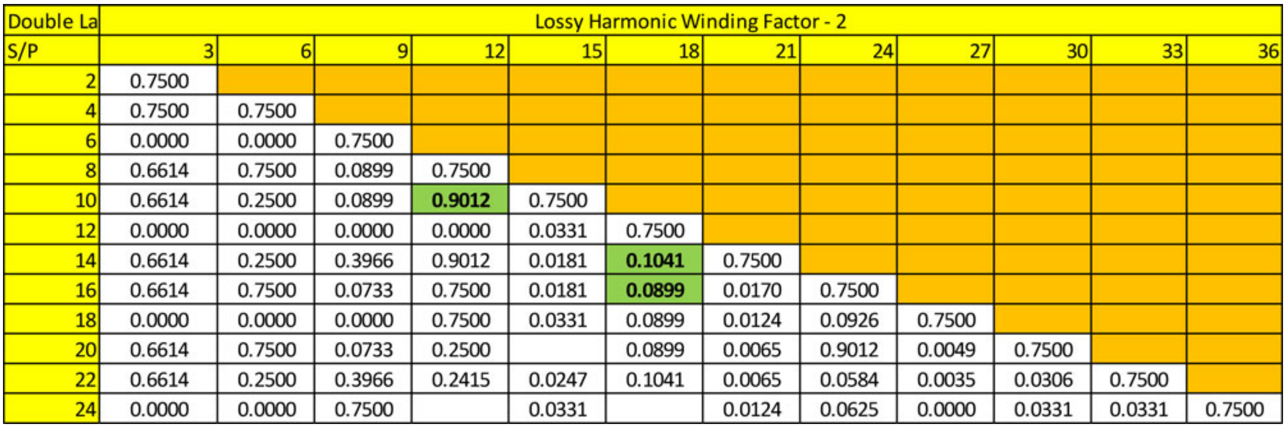
Similarly the winding factors for two-other slot/pole combinations 3/7 and 3/8 slot/pole combinations under two-layer windings are 0.0378 and 0.0607 respectively. The windings factors of the same loss-producing harmonics utilizing *four-layer* configurations are 0.0066 and 0.0207 respectively. These

TABLE IV
WINDING FACTORS OF FIRST LOSS-PRODUCING COMPONENT FOR FOUR-LAYER WINDING CONFIGURATIONS



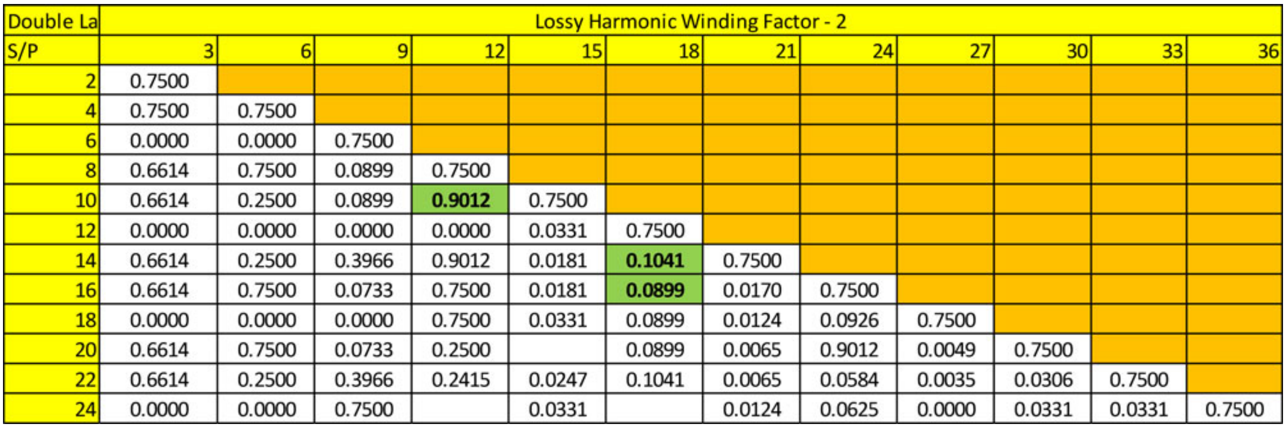
	4-layer	SLOTS											
	S/P	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**30**	**33**	**36**
	2	0.7500											
	4	0.7500	0.7500										
	6			0.7500									
POLES	**8**	0.6614	0.7500	0.0207	0.7500								
	10	0.6614	0.2500	0.0207	**0.0173**	0.7500							
	12			0.0000			0.7500						
	14	0.6614	0.2500	0.0255	0.0173	0.0044	**0.0066**	0.7500					
	16	0.6614	0.7500	0.1123	0.7500	0.0044	**0.0207**	0.0019	0.7500				
	18									0.7500			
	20	0.6614	0.7500	0.1123	0.2500	0.0000	0.0207	0.0016	0.0173	0.0008	0.7500		
	22	0.6614	0.2500	0.0255	0.0647	0.0047	0.0066	0.0016	0.0021	0.0026	0.0146	0.7500	
	24						0.0000						0.7500

TABLE V
WINDING FACTORS OF SECOND LOSS-PRODUCING COMPONENT FOR FOUR-LAYER WINDING CONFIGURATIONS



Double La	Lossy Harmonic Winding Factor - 2											
S/P	3	6	9	12	15	18	21	24	27	30	33	36
2	0.7500											
4	0.7500	0.7500										
6	0.0000	0.0000	0.7500									
8	0.6614	0.7500	0.0899	0.7500								
10	0.6614	0.2500	0.0899	**0.9012**	0.7500							
12	0.0000	0.0000	0.0000	0.0000	0.0331	0.7500						
14	0.6614	0.2500	0.3966	0.9012	0.0181	**0.1041**	0.7500					
16	0.6614	0.7500	0.0733	0.7500	0.0181	**0.0899**	0.0170	0.7500				
18	0.0000	0.0000	0.0000	0.7500	0.0331	0.0899	0.0124	0.0926	0.7500			
20	0.6614	0.7500	0.0733	0.2500		0.0899	0.0065	0.9012	0.0049	0.7500		
22	0.6614	0.2500	0.3966	0.2415	0.0247	0.1041	0.0065	0.0584	0.0035	0.0306	0.7500	
24	0.0000	0.0000	0.7500		0.0331		0.0124	0.0625	0.0000	0.0331	0.0331	0.7500

TABLE VI
FIRST TWO LOSS-PRODUCING COMPONENTS FOR FOUR-LAYER WINDING CONFIGURATIONS



Double La	Lossy Harmonic Winding Factor - 2											
S/P	3	6	9	12	15	18	21	24	27	30	33	36
2	0.7500											
4	0.7500	0.7500										
6	0.0000	0.0000	0.7500									
8	0.6614	0.7500	0.0899	0.7500								
10	0.6614	0.2500	0.0899	**0.9012**	0.7500							
12	0.0000	0.0000	0.0000	0.0000	0.0331	0.7500						
14	0.6614	0.2500	0.3966	0.9012	0.0181	**0.1041**	0.7500					
16	0.6614	0.7500	0.0733	0.7500	0.0181	**0.0899**	0.0170	0.7500				
18	0.0000	0.0000	0.0000	0.7500	0.0331	0.0899	0.0124	0.0926	0.7500			
20	0.6614	0.7500	0.0733	0.2500		0.0899	0.0065	0.9012	0.0049	0.7500		
22	0.6614	0.2500	0.3966	0.2415	0.0247	0.1041	0.0065	0.0584	0.0035	0.0306	0.7500	
24	0.0000	0.0000	0.7500		0.0331		0.0124	0.0625	0.0000	0.0331	0.0331	0.7500

represent a reduction in the components by nearly five and three times respectively, indicating a significant reduction in the rotor losses. It can be also seen that by introducing higher number of layers, the winding factor for the first loss-producing harmonic is reduced for all slot/pole combinations. The level of reduction varies from one combination to another, as indicated before, some are more significant than others. For example, in the 2/5th spp family, the winding factor of the fundamental (loss-producing) harmonic is reduced from 0.067 to 0.0173, while in the ½ spp family the reduction is from 0.866 to 0.75. In the first case, the reduction is four times while the latter only has a reduction of 13.4%. However this reduction is expected to reduce

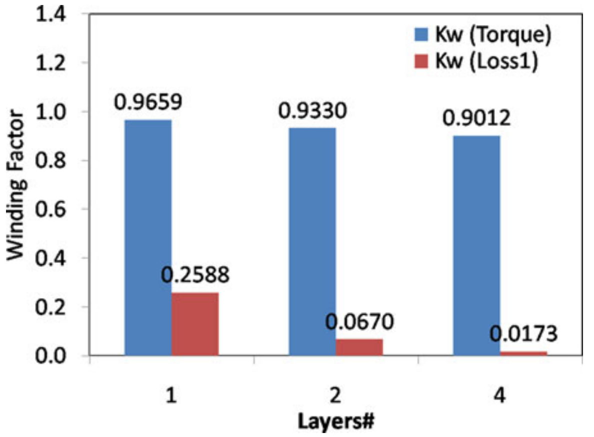


Fig. 4. Winding factors for the 2/5th spp fundamental torque-producing component along with the first loss producing harmonic.

the stator core losses and rotor losses in the machine, thereby improving the machine efficiency.

The aforementioned two effects are counter-acting. A reduction of torque-producing harmonic is expected to reduce the torque density, thereby requiring a bigger machine, while the reduction of the loss-producing harmonic is expected to improve the efficiency hence improving the output mechanical power. The purpose of this study is to identify the slot/pole combinations, which can benefit from the higher number of winding layers, and to understand the effects on torque density, efficiency. Another aspect, which is also investigated, is the torque ripple. The torque ripple is expected to improve with introduction of multilayers.

Since FSCW include a lot of sub- and super-harmonics as previously mentioned, a lot of attention has to be focused on the losses generated by these harmonic components. A good indicator of these losses, is the winding factor of the first (most-dominant) loss-producing harmonic component.

B. Definition of Loss Index and Identifying Optimum Slot/Pole Combinations

The identification of the optimum slot/pole combination having the right number of pole–pairs is based on an index value given to each combination on the basis of their winding factors and operating frequencies.

It is very difficult to come up with a unified method of comparing the different slot/pole combinations based on their performance since without the complete design, the comparisons would be meaningless. Nevertheless the effect of fundamental winding factor along with the effect of frequency, winding factors of the subharmonics cannot be ignored. One way to compare would be to assign weighing factors to these parameters and choose the configuration with the best index. However such an index does not bring out the differences between the designs without the correct baseline. For the present analysis, since the winding factor is already per-unitized to unity, the other factors of fundamental frequency, loss-producing harmonic frequency along with the winding factor of the same are accounted for, based on the baseline of ½ slot/pole configuration. The frequency of the ½ spp configuration (having four poles) at top speed is about 500 Hz, whereas the frequency of the first loss-producing harmonic, which is incidentally a subharmonic, is about 250 Hz. The winding factor for the subharmonic in one of the preferred configurations in literature, namely the 2/5 slot/pole configuration has a winding factor of 0.017 for the subharmonic, which is chosen as the per-unit value for the frequency of the loss-producing harmonic.

The rating introduced for each slot/pole combination is given as follows:

$$\begin{aligned} K = {} & k_1 K_{w1} + k_{\text{freq1}} \\ & + k_{\text{loss1}} \frac{0.02}{K_{w-\text{loss1}}} \\ & + k_{\text{freq-loss1}} \frac{250}{\text{freq}_{\text{loss1}}} \end{aligned} \tag{1}$$

where k_1 is the weighing factor for the synchronous winding factor, K_{w1} is the synchronous winding factor, k_{freq1} is the weighing factor for the frequency of the synchronous winding factor, freq1 is the frequency of the synchronous winding factor, k_{loss1} is the weighing factor for the winding factor of the first loss producing subharmonic, $K_{w-\text{loss1}}$ is the winding factor of the first loss producing subharmonic, $k_{\text{freq}-\text{loss1}}$ is the weighing factor for the frequency of the first loss producing subharmonic and $\text{freq}_{\text{loss1}}$ is the frequency of the first loss producing subharmonic.

The aforementioned objective function is aimed at “pointing out” designs with high winding factors for synchronous harmonic component (for torque density) and low winding factor for dominant loss-producing harmonic component (for higher efficiency).

In order to achieve the best configuration, the objective function is related to the power density and efficiency through the means of winding factors and frequencies. The winding factor of working harmonic relates to power density. Higher the value of the winding factor, higher is the power density of the resulting design. The frequency, on the other hand, relates to the efficiency of the motor. Higher is the frequency, the higher are the core losses in the machine and lower is the efficiency. The winding factors of first two loss-producing harmonics also relate to efficiency. The higher are these winding factors, lower is the efficiency of the motor. Torque ripple in fractional-slot windings is not considered to be a problem and is not included in the analysis.

As said previously, different range available for the slot/pole combinations determines each of the base quantities. The variation of the winding factor is from 0.2 to unity, with the higher values being preferred over the lower values. The base value is chosen as unity for the winding factor. Additional stress is placed on the power density by assigning a great weight to the winding factor, i.e., $k_1 = 0.85$.

The losses in the machine are defined by the synchronous frequency at top speed as well as the winding factor and frequency of the first loss-producing harmonic. Since the frequency and the winding factor have a negative effect on

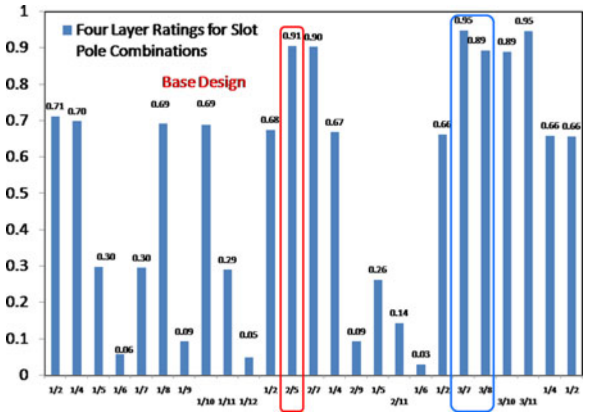


Fig. 5. Ratings for the spp combinations based on winding factors and frequencies.

Fig. 6. Stator and rotor of the 12-slot/10-pole two-layer prototype.

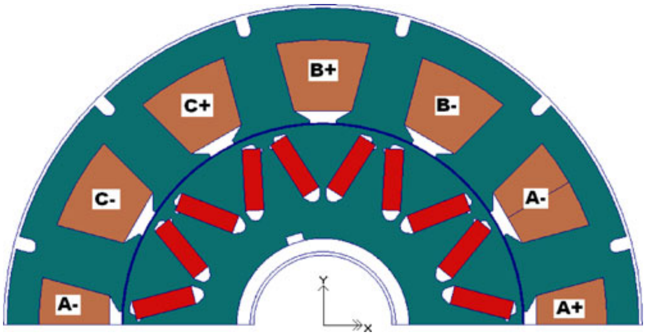


Fig. 7. Cross-section of single-layer (1-*layer*) winding with V-shape for a 10-pole, 12-slot design belonging to the 2/5 spp family.

efficiency, the objective function is able to include their sensitivity by taking the inverse of the winding factor of the loss producing harmonic, similar to case of the inverse of the winding factor of the loss producing harmonic being included in the objective function. The possibilities that the winding factor of the loss-producing harmonic can be very low, a constraint of 0.02 was placed on the maximum limit on the total weight arising out of the winding factor of the loss-producing harmonic.

The base value of the frequency of the fundamental harmonic is based on the lowest frequency in the slot/pole combinations range. The ½ spp configuration with two poles, three slots has the lowest frequency of 466 Hz, and is used as the base for weighing the fundamental winding factors. The corresponding frequency of the loss-producing harmonic is 250 Hz, which is chosen as the base for the frequency of the loss-producing harmonic. The final ratings for the spp combinations are plotted in Fig. 5. The slot/pole combination representative of the spp values in the figure are highlighted (brown rectangles) in Table I. It is to be noticed that as previously mentioned, the slot/pole combinations with unbalanced radial forces are dropped in the figure for final ratings. The spp combinations that emerge as the best candidates are the 2/5th, 3/7th, and 3/8th. The slot/pole combinations of 2/7, 3/11, and other slot/pole combinations suffer from a major handicap. These slot/pole combinations have two loss-producing subharmonics, compared to other spp combinations of 2/5th, 3/7th, and 3/8th (which only have the fundamental harmonic has the loss producing harmonic).

The main criteria for choosing these slot/pole combinations were based on the power density (mainly the synchronous winding factor) as well as efficiency (mainly the effect of frequency as well as the winding factors of the most dominant loss-producing harmonic components). This is the essence of the index defined in (1) as well as the ratings shown in Fig. 5.

One of the first guidelines beyond the scale proposed is the presence of the unbalanced forces. The combinations in each of the slot/pole combinations chosen must have even number of slots, which according to several authors indicates the absence of such unbalanced radial forces. The order and frequency of the vibration modes vary based on the designs but it is still believed that the evaluated designs must not suffer from vibration issues. This has been seen in the testing of the machine presented here belonging to the 2/5 spp family.

Additionally it is known that in FSCW machines, one of the main disadvantages is the presence of the rotor losses, because excluding the 1/2 spp configurations, all other combinations have one or more subharmonics. To find a compromise between the high synchronous winding factor and the low winding factors for loss-producing harmonics, the cases where *the number of slots is more than the number of poles* [13], [16] are to be dropped. This is because in these families, there is not one but two subharmonics, which can lead to high rotor losses. This is considered as a second guideline in choosing a correct slot/pole combination.

Choosing the aforementioned index helps to differentiate between the designs having different pole–pairs within the same slot/pole family. For example, the 4-pole 6-slot configuration would have a better index than the 8-pole, 12-slot configuration just because the fundamental frequency in the latter is double than that of the former. This justifies choosing designs with better efficiency belonging to the same slot/pole family.

Beyond the index proposed, the aforementioned two guidelines are needed to choose machine designs with proper slot/pole combinations.

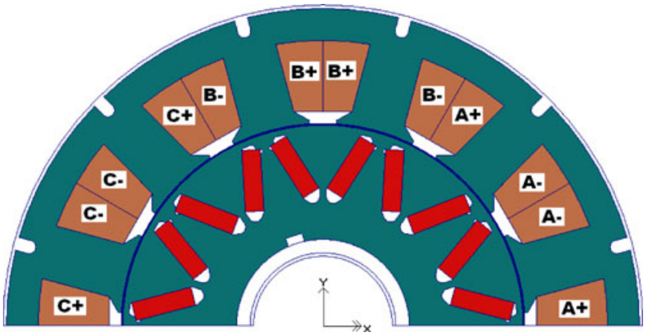


Fig. 8. Cross-section of double-layer (2-*layer*) winding with V-shape for a 10-pole, 12-slot design belonging to the 2/5 spp family.

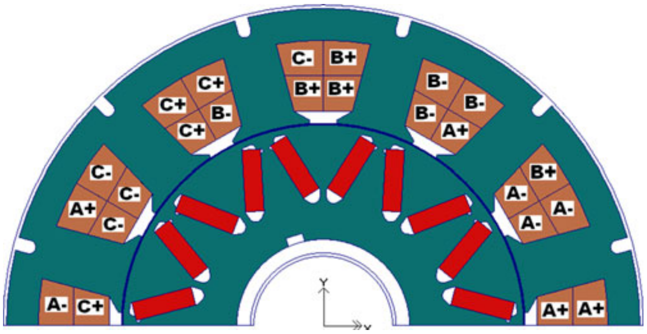


Fig. 9. Cross-section of four-layer (4-*layer*) winding with V-shape for a 10-pole, 12-slot design belonging to the 2/5 spp family.

TABLE VII
SUMMARY OF KEY FREEDOMCAR ADVANCED TRACTION MOTOR PERFORMANCE REQUIREMENTS [14]

Parameter/Metric	Value
Peak Power @ 2800 r/min	55 kW
Maximum speed	14 000 r/min
Continuous power	30 kW
Mass power density for total machine	> 1.6 kW/kg
Vol. power density for total machine	> 5.67 kW/l
Constant power speed ratio	5:1
Maximum phase current	400 Arms
Peak line-to-line back-emf @ 2800 r/min	600 V
Efficiency at 20% rated torque up to the max. speed	> 95%

C. Design Procedure

A fully-optimized two-layer electric machine belonging to the 2/5th spp family is designed, built and tested for a peak power of 55 kW at 2800 r/min and a top speed of 14 000 r/min, while providing a continuous power rating of 33 kW from 2800 r/min to 14 000 r/min. The motor has gone through several iterations of electromagnetic, mechanical and thermal analysis, with emphasis on the highest torque density, while being mechanically feasible at the top speed of 14 000 r/min, and coolable throughout the entire speed range. This prototype is shown in Fig. 8. The design requirements [14] of the machine are based on the FreedomCar specifications and are given in Table VII.

This design is able to satisfy most of the requirements in Table VI. Meeting the efficiency requirements has been one of the most challenging aspects of the machine design and has been difficult to meet due to the issue of higher frequencies in these machines. More of the experimental results for the same machine is shown in the appendix.

Single- and four-layer designs of the machines in the 2/5th spp family have been developed. They have the same effective number of turns as the two-layer prototype. A slight variation in the permanent magnetic flux linkage (and characteristic current) is seen due to this constraint due to the variation in the winding factor (Table VIII). The cross-sections of the single layer, two layer and four layer designs are shown in Figs. 7–9 respectively. These optimized designs will be used to highlight the tradeoffs between the different number of layers as will be discussed in Section III.

Furthermore, to highlight the tradeoffs between different slot/pole combinations, a simplistic approach is taken. Designs belonging to different slot/pole combinations are modeled using circular bridges. The bridges are not optimized as in the case of the 12-slot/10-pole 2/5th spp prototype previously mentioned. New sets of designs for 2/5th spp as well as two- and four-layer designs for 3/7th and 3/8th spp configurations have been developed based on circular bridges.

The losses in the machine are calculated as the sum of iron, copper and magnet losses, which in turn are based finite element predictions. The estimation of iron loss is done on an element-by-element basis, where in the flux density waveform is decomposed into the individual harmonics along with the application of the Steinmetz formulation on each harmonic.

It is expected that the trends in terms of power density, efficiency would remain the same for unoptimized bridge designs. The tradeoffs between the various slot/pole combinations will be discussed in Section IV.

III. COMPARISON OF DIFFERENT NUMBER OF LAYERS

This section will quantify the tradeoffs between the three 2/5th spp designs referred to in the previous section and shown in Figs. 7–9.

The effect of the number of layers in terms of peak power density [kW/kg], under peak power conditions of 400 Arms, is shown in Fig. 10. This is a contradictory result to the expectation that the power will reduce with the introduction of higher number of layers. This can be mainly attributed to the improvement of the saliency and hence reluctance torque within the machine (mainly due to reduced saturation effects). This is supported by the fact that the maximum torque per amp point lies at a current angle of 20° in the four-layer winding machine compared to 10° in the single- and double-layer windings (Fig. 11). This trend indicates improvement in reluctance torque, consistent with the findings that reluctance torque improves as the design gets closer to a distributed winding. A significant improvement of 5.2% is seen in the torque density while moving from a double-layer to a four-layer design.

TABLE VIII
SUMMARY OF KEY METRICS BETWEEN DIFFERENT DESIGNS

Design	PM flux linkage [mWbrms]	Saliency at peak power [pu]	Characteristic current [Arms]	Magnet content [kg]
2/5 spp – 2 layer	39.5	1	180	2.5
2/5 spp – 4 layer	38.2	1.05	150	2.7
3/7 spp – 2 layer	40.6	0.87	180	2.6
3/7 spp – 4 layer	38.2	0.87	160	2.6
3/8 spp – 2 layer	42.0	0.79	180	2.7
3/8 spp – 4 layer	41.4	0.81	160	2.6

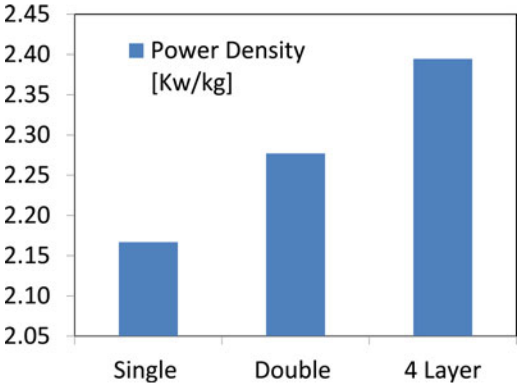


Fig. 10. Power density as a function of number of layers.

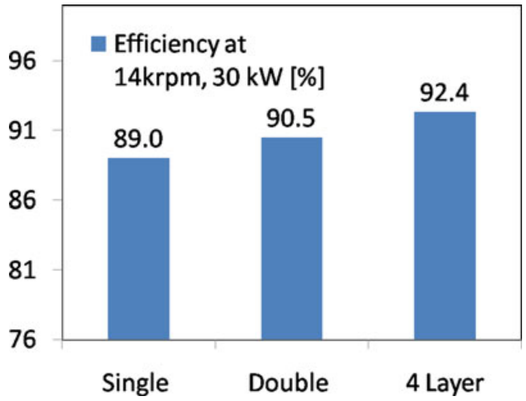


Fig. 12. Improvement of top-speed efficiency with multiple layers.

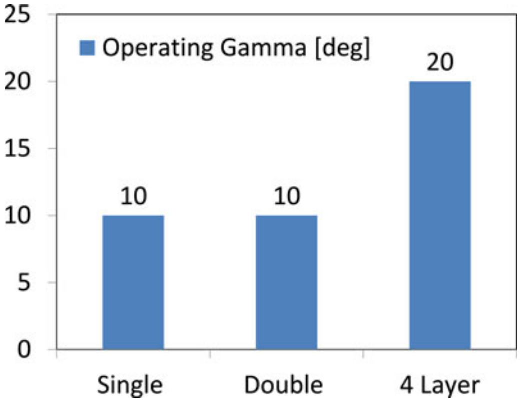


Fig. 11. Variation of current angle gamma at maximum torque per amp point.

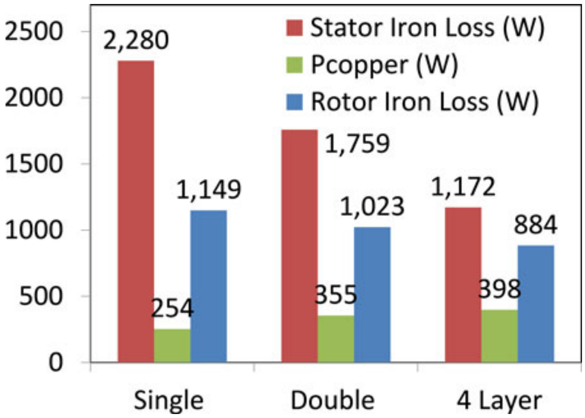


Fig. 13. Reduction of iron losses and increase in copper losses with multiple layers.

The improvement in efficiency at the top speed of 14 000 r/min (1166 Hz) is about 1.9% as shown in Fig. 12. This is considered as a significant improvement at high speeds. The improvement is possible by the reduction of iron losses, which in turn arises from the reduction in fundamental (first loss-producing harmonic) winding factor/magnitude, as shown in Fig. 13. On the other hand, an increase in copper losses is seen due to the increase in required d-axis current required to satisfy the voltage constraints. Even though the q-axis current remains very much the same, as shown in Fig. 14, the decrease in machine phase inductance requires additional d-axis current to meet the voltage specifications of the machine at top-speed.

As expected, going to higher number of layers, the torque ripple is reduced, mainly due to the reduction in the winding factors of all the additional (other than the torque-producing) harmonics in the winding function. A reduction of 13.5% is seen, going from a single layer to double layer at peak power of 57 kW, while a further 1.5% reduction is obtained going from a double layer to a four layer winding design as shown in Fig. 15.

IV. COMPARISONS OF DIFFERENT SLOT/POLE COMBINATIONS AND LOSS INDEX

As previously mentioned, in order to compare different slot/pole combinations, simplified designs with circular (un-optimized) bridges were developed. New 2-layer and 4-layer 2/5th spp with circular bridges have been designed (Fig. 16).

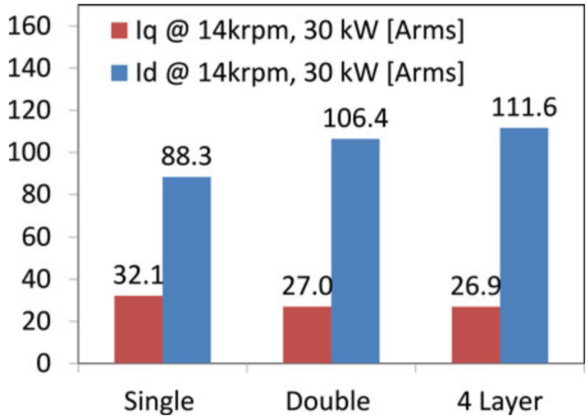


Fig. 14. Operating point of Id, Iq at 14 k r/min and 30 kW, in different number of layers.

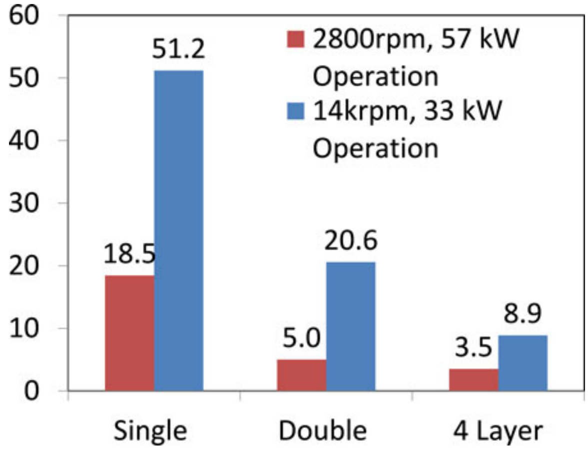


Fig. 15. Improvement of torque ripple [pc] with multiple layers.

MagNet by Infolytica has been used for all the electromagnetic FEA while ANSYS has been used for both the thermal and mechanical analyses.

A single-layer winding with a good winding factor (0.902) can be designed in the particular case of 14 poles and 18 slots. This design has a subharmonic, whose magnitude is 18.9% of the fundamental and has lower efficiency than the double layer winding. The tradeoffs from single layer to double layer windings are understood in the previous slot/pole combinations, and hence this design has not been considered in this study. Only 2-layer and 4-layer designs were developed (Fig. 17).

The design of the machines is based on the constraints of equal magnetic flux linkage and similar current and current density limits. The rotor design and number of turns are varied to achieve the same open-circuit magnet flux linkage and characteristic current as the machines belonging to the 2/5th spp family (Table VIII). The design procedure is seen to lead to machines with lower number of turns where the drop in the magnetic flux linkage is compensated by the deeper magnets within the rotor. The total number of turns is kept the same while going from a two-layer to a four-layer design. There is a slight reduction in flux linkage, reaching up to a couple of percent in this family.

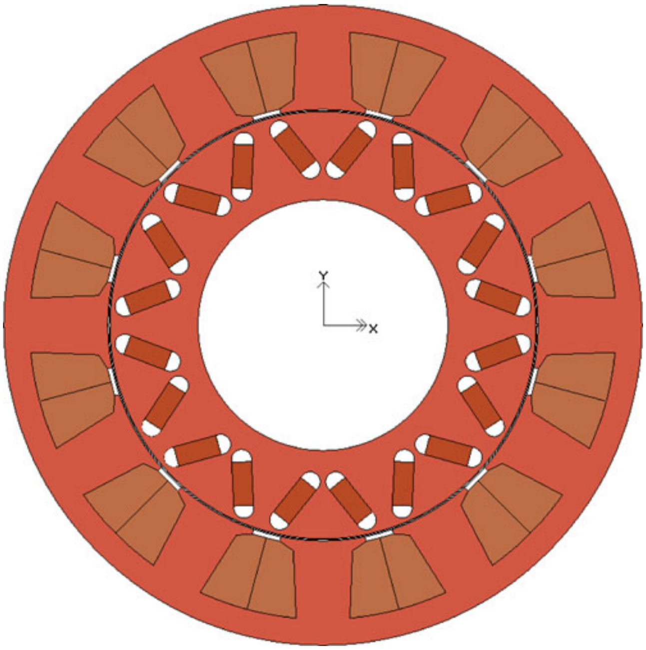


Fig. 16. Cross-section of 10-*pole*, 12-*slot* machine with 2-*layer* winding belonging to 2/5 *spp* family.

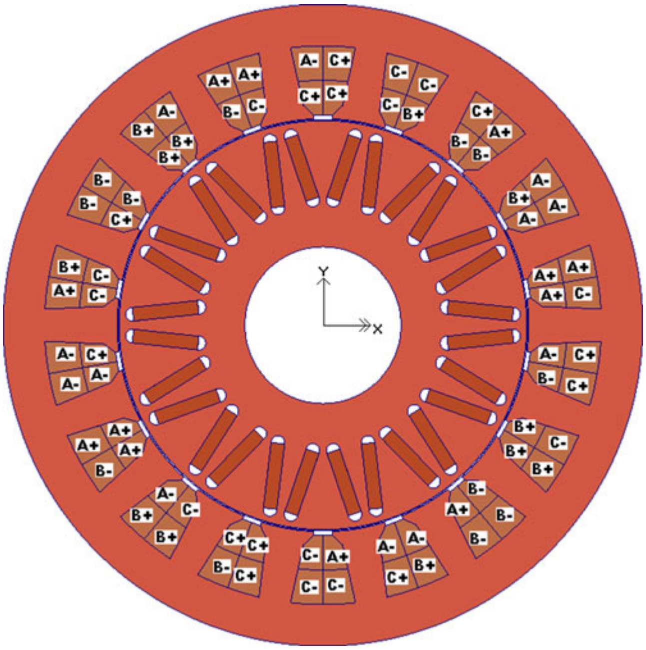


Fig. 17. Cross-section of 14-*pole*, 18-*slot* machine with 4-*layer* winding belonging to 3/7 *spp* family.

Similar reasoning is applicable to the design of electric machines belonging to the 3/8 spp family. The final cross-section of the two-layer machine is shown in Fig. 18.

The magnet content shown in Table VIII, shows that the amount of magnet material is kept nearly the same between different designs. This is one of the key metrics kept constant between the designs.

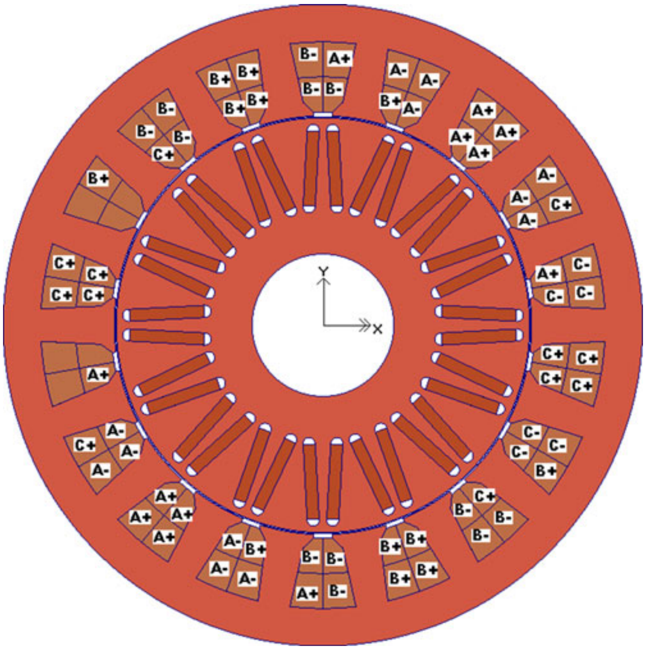


Fig. 18. Cross-section of 16-*pole*, 18-*slot* machine with 4-*layer* winding belonging to 3/8 *spp* family.

A comparison of saliency for the various designs is also presented in Table VIII. It can be seen there is a slight improvement in saliency while going from double layer to four layer in the 2/5th spp. However the improvement in saliency is limited in the 3/7th and 3/8th spp due to the presence of two subharmonics.

It is also worth mentioning that this is a simple Lq/Ld calculation which does not take into consideration the fact that the magnet flux linkage is not constant as well as cross-saturation effects. In order to capture these two effects, permeance freeze is needed.

A. *Results for 3/7 spp*

The power density in the 3/7 spp family presents an interesting view. Although the 3/7 slot/pole family has a lower winding factor (kw = 0.85) compared to the 2/5 slot/pole family (kw = 0.90), the reduction in number of turns allowed for an increase in magnetic loading of the machine. Such an increase was possible due to deeper magnets, allowing an increased power density.

While moving from two-layer design to a four-layer design, where the iron and magnet structure is kept the same, from Fig. 19, the power density improves by *5%*. This improvement has been explained before, as the link to the improvement of saliency with an increase in number of layers. Additionally due to the reduction of the loss-producing components, the efficiency improvement shown in Fig. 20 is about *2%* at the top speed of 14 000 r/min. A reduction of 600 W is achieved, 200 W of which occur on the rotor side. This reduction is important from the point of view of the rotor cooling mechanism, as explained previously.

The comparison of the partial load (20% of rated torque) efficiencies of the designs belonging to the 2/5 spp and 3/7 spp families are shown in Figs. 23 and 24 respectively. It can be clearly seen that the efficiency improvement is observed at the higher speeds, while at the lower speed the improvement in the iron losses is minor.

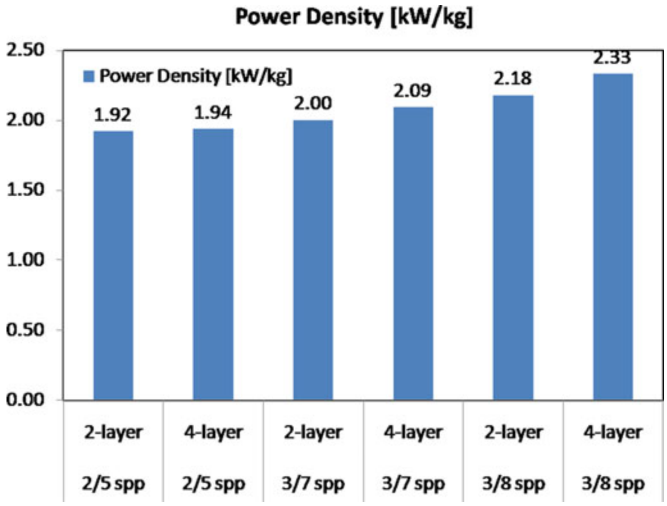


Fig. 19. Power density variation between b different slot/pole combinations including the variation of number of layers.

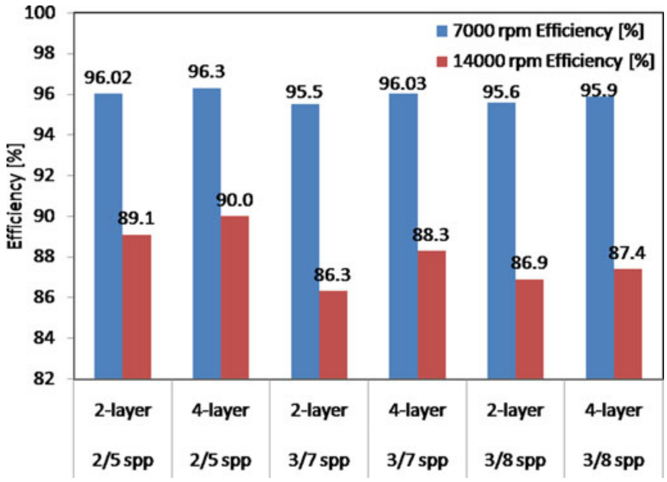


Fig. 20. Comparison of efficiencies at 14 kr/min and 7 kr/min between different *unoptimized* slot/pole combinations and number of layers.

B. *Results for 3/8 spp*

A similar trend is seen in the 3/8 spp family. However this trend is more significant in this family. The power density improvement is about 10%, while moving from a two-layer to a four-layer design. The efficiency improves by about 0.5% at top speed.

C. *Power Density*

The comparison of power density across the different slot/pole combinations is shown in Fig. 19. It can be seen that the 3/8th spp has the highest power density in this particular case.

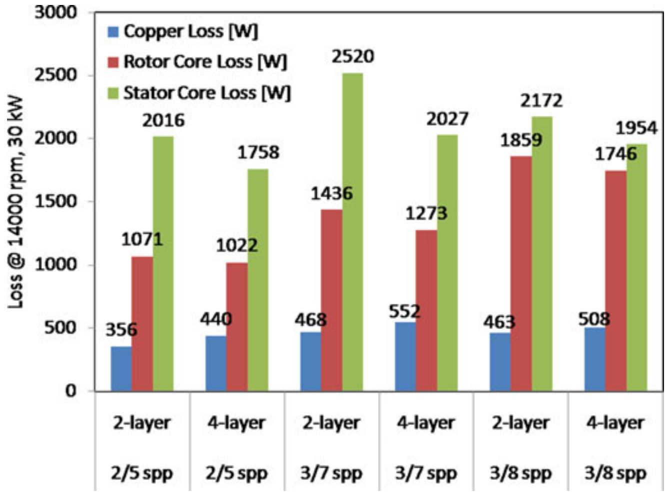


Fig. 21. Loss comparison between different *unoptimized* slot/pole combinations at 14 000 r/min, 30 kW.

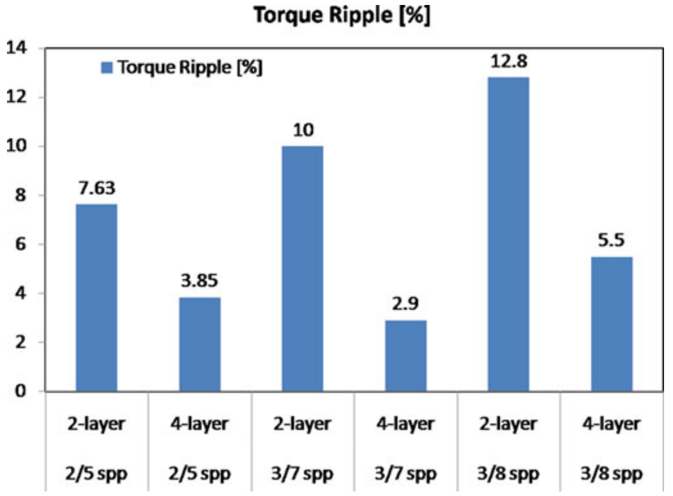


Fig. 22. Comparison of torque ripple between different *unoptimized* slot/pole combinations at 2800, 55 kW.

The four-layer winding for each of the slot/pole combinations improves the power density.

D. Efficiency and Losses at High Speed

Fig. 20 shows the comparison of the efficiencies of different slot/pole combinations at the top speed of 14 000 r/min as well as at 7000 r/min, while delivering the rated power of 30 kW. It can be seen that there is an improvement in efficiency going from 2- to 4-layers. The 2/5th spp has the highest efficiency. The breakdown of the losses is shown in Fig. 21. The increase in copper losses from two-layer to four-layer designs is an indication of the lower winding factor, while the improvement in the losses is mainly due to reduction in the core losses. The effect of frequency is seen in the reduction of the efficiency of the 3/7th and 3/8th spp combinations compared to the 2/5th spp designs. These slot/pole combinations show significantly higher core losses compared to the 2/5th spp.

On the other hand, at lower frequencies at 7000 r/min, the different slot/pole combinations can be equally efficient. The results shown in Fig. 20, depict that the efficiencies can be in excess of 95% while delivering the rated power of 30 kW.

E. Torque Ripple

Comparison of the torque ripple at the corner speed of 2800 r/min while delivering the peak power is shown in Fig. 22. The 2/5th spp combination shows the lowest ripple for two-layer designs compared to the 3/7th and 3/8th spp combinations while the 3/7th spp shows the lowest torque ripple among the four-layer designs. Also the reduction in torque ripple with introduction of multiple layers is clearly seen.

F. Selection of spp Combination

Based on the power density picture, the machines with 3/8th spp combination present the most power dense machines. The use of higher number of layers can help increase the power density by an additional 1%, without losing the torque performance.

TABLE IX
RATINGS OF DIFFERENT MACHINES

Design	Rating
2/5 2-layer	1.0
2/5 4-layer	1.04
3/7 2-layer	0.88
3/7 4-layer	1.04
3/8 2-layer	1.008
3/8 4-layer	1.11

In machines with high-speed requirements, i.e., with speeds in excess of 10 k r/min or with frequencies reaching close to a 1 kHz, the efficiencies in 3/8th spp can be significantly lower than the 2/5th spp machines. This is partly due to the higher frequencies in the machines belonging to the 3/8th spp combination. This tilts the choice in favor of the 2/5 spp family.

However in applications of hybrid electric vehicles demanding higher power than 55 kW, i.e., in machines designed for lower speeds, the choice is different. Fig. 20 shows the efficiencies of these machine configurations at 7000 r/min. The best efficiency is achieved with higher number of layers, while the efficiencies of the 3/8th spp machines are quite close to that of the 2/5th spp machines. If the top frequencies are limited in machines, to much less than 1 kHz, it is possible that the 3/8th spp family can be as good of a choice as the 2/5th spp family.

G. Loss Index

Initial criteria of the loss indices showed that 3/7th spp machines had a higher rating compared to both 2/5th and 3/8th spp combinations. With the final results of power density and efficiency, the new ratings of the different slot/pole combinations are estimated. The 2/5th spp 2-layer family is considered as the base. Updated ratings for all the designs are given in Table IX.

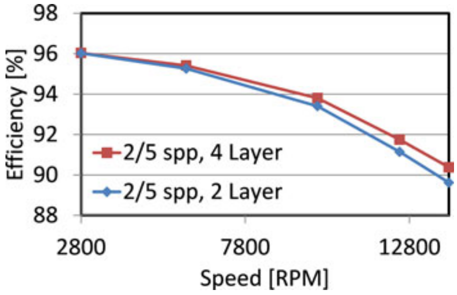


Fig. 23. Comparison of partial load efficiency for 2- and 4-layer windings with 2/5 spp design.

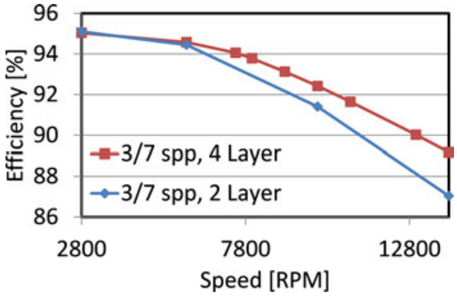


Fig. 24. Comparison of partial load efficiency for 2- and 4-layer windings with 3/7 spp design.

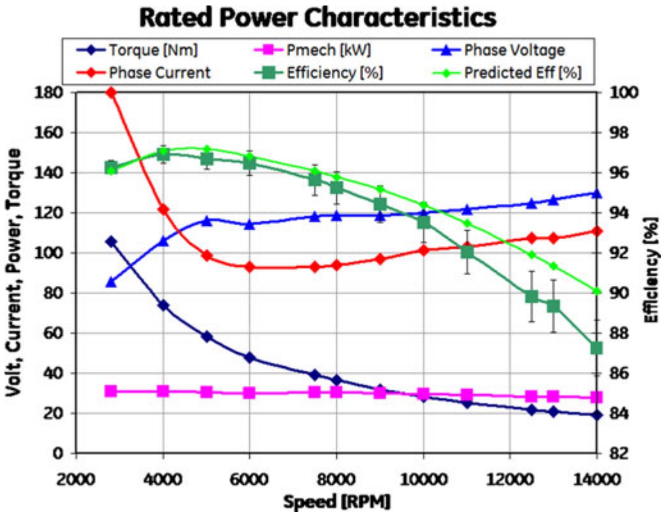


Fig. 25. Experimental results from the FSCW-IPM machine under rated load condition.

The 3/7th spp family with 2-layer windings has a lower rating, while the 4-layer has equal rating as the 2/5th spp machines. However the 3/8slot/pole design with 4-layer enjoys a much higher rating than the other slot/pole combinations, indicating that it is another good choice.

These ratings are different from the initial ratings, showing that 3/8th spp combination can be more promising, while the 3/7th spp combination is comparable to the 2/5th spp combination. However the initial ratings have been satisfying in identifying the slot/pole combinations with promising power densities and efficiencies.

Concluding, it is important to understand that the index as defined in (1) is a "directional" index to point to the potential "optimum" slot/pole combinations. The additional guidelines regarding the unbalanced forces and the presence of additional subharmonics have to be considered to reach an "optimum" design. It is important to know that that it is extremely difficult to try to come up with a modified general index that is accurate for all slot/pole combinations based on the actual analysis.

V. CONCLUSION

The effect of increase in number of winding layers on the winding factors of the torque-producing and the first loss-producing harmonics in FSCW interior PM machines is studied. The optimum spp combinations with a high winding factor for a torque-producing harmonic, but low harmonic content, with four winding layers are identified. The paper shows an improvement in power density, reluctance torque, efficiency and torque ripple going from single to double to four layer winding configurations. Various tradeoffs involved as well as analysis of additional identified optimum spp combinations have been presented. Optimization of each design is expected to yield more power dense machines.

The novel aspects of this paper are given as follows:

1) the impact of number of layers in the case of FSCW windings in IPM machines has been investigated, it has been pointed out that most of the previous literature exists only for the SPM machines;
2) a criterion and an index for choosing the optimum slot/pole combination has been presented;
3) various tradeoffs involved have been highlighted.

APPENDIX

A. Experimental Results of Two-Layer Winding:

A. Experimental Results of Two-Layer Winding: Detailed experimental results for the design with two-layer winding with an interior permanent magnet rotor belonging to the 2/5 spp family have been completed and will be presented here. The goal of the comparison of the predicted and measured data has been to build the confidence in the design and the analytical processes used for the other designs. Some of the results are presented in this section, with more details available in Reddy [15].

The experimental results under rated power are shown in Fig. 25 while the experimental results under the partial-load 20% rated torque conditions over a speed range of 1400 to 14000 r/min are shown in Fig. 26. A higher difference is seen in the predicted and experimental efficiencies under the partial-load conditions. The machine is able to exceed the partial-load minimum efficiency requirement of 95% at the lower speeds, while it is able to deliver at least 93% efficiency up to a speed of 8000 r/min. The efficiency drops to ~87% at 14 000 r/min. One of the major suspects for causing the lower efficiency is the presence of the mechanical losses in the system along with the current regulation. Since the FSCW-IPM machine has more harmonics in the back-emf waveform, pure sinusoidal current

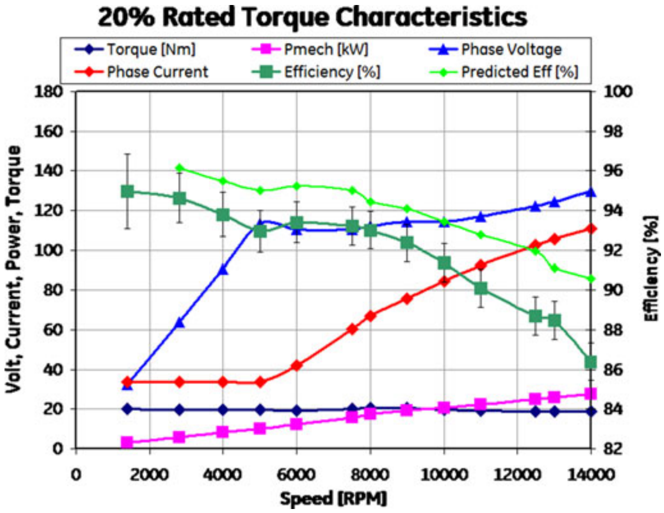


Fig. 26. Experimental results from the FSCW-IPM machine under partial-load conditions.

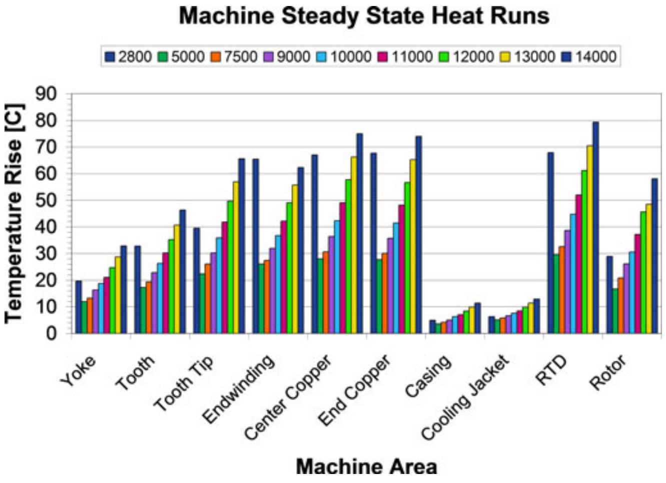


Fig. 27. Measured temperature rises in various locations in the FSCW-IPM machine.

regulation might not be enough to achieve the required partial-load efficiencies.

As part of the machine test sequence, steady-state heat runs were performed on the FSCW-IPM machine from 2800 to 14 000 r/min under rated load conditions. The steady-state temperature rise in the machine measured in different locations in the machine (yoke, teeth, teeth-tip, end-winding, center of the windings, copper end region in the slot, the casing, the cooling jacket, and the rotor) are shown in Fig. 27. The machine was able to successfully withstand the temperature rise in the machine under all the operating conditions, with the top temperatures being within the insulation limits. The maximum temperature rises was seen in the copper regions, mainly the end-winding portion along with the slot regions inside the slots.

With a coolant temperature of 105 °C, the end-winding temperature would reach approx. 175 °C–185 °C, well within the 220 °C–240 °C temperature limits for the Class C insulation selected for the machine's magnet wire. Although the teeth-tips also reach similar temperatures under some of the operating conditions, heat extraction through the laminations is easier since there is no insulation in the thermal path.

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