Evaluation, Application and Comparison of a Double-Rotor Toothed Toroidal Winding Wind Generator Over a Wide Power Range

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***Abstract*—The double rotor, toothed, toroidal winding permanent magnet machine is not a well known concept and has received very limited attention in literature. In this study the concept is proposed for use as a direct-drive wind generator. The permanent magnet generator is optimised by means of finite element analysis over a wide range of wind power levels. For each power level the optimum design is compared with optimum non overlap winding and conventional overlap winding permanent magnet machine designs. Although the electromagnetic design of the generator is the main focus of the paper, some of the implementation issues are also discussed. An existing 15 kW double rotor permanent magnet wind generator is modified to include a toroidal winding, which is used as a case study. Both simulated results and practical measurements in the laboratory for the 15 kW case study toroidal winding PM generator are presented in the paper.**

I. Introduction

Although most installed wind turbine systems make use of the geared doubly-fed induction generator and partially rated converter topology, direct-drive wind generators are utilised in several new installations in order to decrease the number of components in the drive train. This eliminates the maintenance issues associated with gearboxes, which should, thus, in turn reduce the operation and maintenance (O&M) costs of the wind turbine system. Utility scale direct-drive wind turbine systems make use of both wound synchronous generator (WSG) and permanent magnet synchronous generator (PMSG) topologies, while small-scale wind generators mostly utilise directly turbine mounted PMSGs. However, due to the current high price of permanent magnet (PM) material, PMSGs are losing their attractiveness, due to these types of systems currently being the most expensive [1]. Due to the high costs associated with direct-drive utility scale PM wind generators, many are also considering high speed and medium speed PM wind generators, as for example in [2]. Some manufacturers are also again installing the conventional squirrel cage induction generator and multi-stage gearbox due to the low initial capital cost of this system, with the generator connected to the grid via a full rated converter, in order to comply with the relevant grid code specifications.

From the discussion above it is, thus, evident that in order for direct-drive PM wind generators to remain competitive the cost of these generators needs to be reduced. Several works on the design and comparison of direct-drive PM generators with regard to other drive-train topologies are available in literature as for example in [3]–[9]. The major issues identified in the design and implementation of direct-drive PM wind generators are the high cost and volatility of PM prices, the high active mass and also high structural mass at higher power levels, as well as the large size which makes assembly, installation and transport difficult. It is, thus, essential that the mass and PM content of these generators be made as low as possible.

Dual rotor PM machine topologies have been proposed for wind generators before as for example in [7] and [10]. However, in the case of conventional overlap winding machines, the large end-windings could make it difficult to assemble the machine, which means that the eventual configuration might not be at the optimum machine dimensions. Many dual rotor PM machine topologies also have the disadvantage of a larger effective airgap. In this case it might be better to go for the toothed toroidal type of topology such as in [11], [12] and more recently in [13] and [14] as proposed for wind generators.

In this paper the novel toothed toroidal winding wind generator is evaluated with respect to other direct-drive wind generator topologies such as conventional overlap winding and non overlap winding PM wind generator configurations. Although this generator type has been proposed before for direct-drive wind generators as in [13] and [14], there is a lack of a clear indication in literature as to the applicability and advantages of this generator type with regard to other topologies currently in use. To obtain a better indication regarding the applicability of the toroidal winding wind generator, optimisation results are presented over almost the entire wind turbine power range. Simulation results and practical laboratory measurements are given for a case study toroidal winding wind generator. This generator is constructed by modifying an existing 15 kW double rotor direct drive PM wind generator. The unmodified generator is the same prototype machine as evaluated in [10].

II. Novel Toothed Toroidal Winding Concept

Normally toroidally wound coils are wound around a steel cylinder with the stator being toothless. This allows for easier manufacturing, but the drawback is a large airgap that requires more PM material. In this study a slotted stator configuration is used with slots on both the inner and outer diameters of the stator, with a common stator yoke as shown in Fig. 1(a). The machine is assembled in such a way that two opposing magnet polarities face one another. The flux from the bottom magnet thus links the bottom conductor, and the flux from the top magnet links the top conductor. Fig. 1(b) shows a conventional double rotor topology, where the flux of the bottom and top magnets link through the stator section of the machine.

Fig. 2(a) shows an example of a more conventional type single rotor, double layer, non overlap winding PM machine, of which the design and evaluation is more thoroughly covered in [14]. Fig. 2(b) shows a double rotor variant of this winding type as is evaluated in [10]. An example of the toroidal winding topology considered in this study is shown in Fig. 2(c), with Fig. 2(d) showing the phase layout of this winding type when utilising six slots per pole.

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A significant advantage of the double rotor toroidal winding PM generator is the fact that none of the coils are overlapping which means that the size of the end-windings is significantly reduced as when compared to conventional overlap windings. The copper losses and mass are, thus, reduced accordingly. Furthermore, segmentation, which is especially a consideration for large wind generators, should not be a problem in this type of winding due to no overlapping coils. Due to this generator utilising a three phase winding layout, it should also have a much better torque performance when compared to non overlap winding topologies. Currently it is difficult to comment on the manufacturability of the double rotor toroidal winding generator as this type of configuration has yet not been used for wind generators, especially for large diameter generators.

Although this machine has been practically evaluated in literature, such as in [11] and [12], and good results were obtained, the reason why it has not received widespread adoption in industry, might be that it has only been implemented for low pole number machines. At low pole numbers the use of this type of configuration is questionable due to the large common yoke that would be required, which increases the end-winding length and reduces the airgap diameter of the bottom PM rotor. Furthermore, if the common stator yoke saturates, unwanted coupling effects might occur between the top and bottom PM rotors.

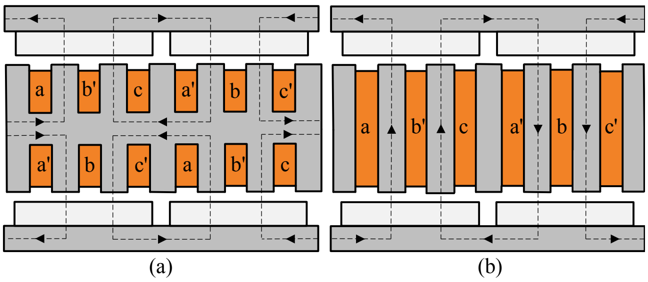
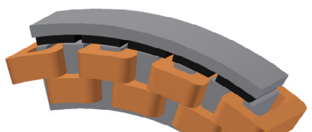
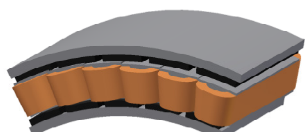


Fig. 1. Flux paths for (a) new concept toothed toroidal winding and (b) conventional type, double rotor PM machine topologies.



(a)



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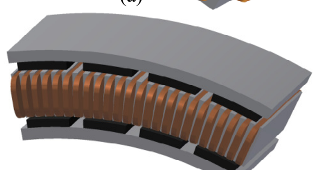

(c)

a	a	b'	b'	c	c
a'	a'	b	b	c'	c'

(d)

Fig. 2. (a) Single rotor and (b) double rotor non overlap double layer winding and (c) new concept double rotor toothed toroidal winding PM wind generator topologies. (d) Phase layout diagram for the toroidal winding over one pole.

III. Design Specifications and Methodology

In previous studies of the toroidal winding PM wind generator, such as in [14], a comparison between the different winding configurations is only done at the 15 kW power level. In this study a comparison is done over almost the entire wind turbine power range, in order to get a much broader and indicative idea of the applicability of the new concept toroidal winding PM wind generator.

A. Optimisation Methodology

A study similar to the one in this paper is reported in [15] where a new concept wind generator is compared over the power range from 30 kW to 3 MW, which includes most of the wind turbine power range definitions, small scale, medium scale and utility scale. Although there are many definitions for the power ranges of small scale wind turbines, small-scale systems are mostly considered as anything below 100 kW, with around more or less 1 kW and less considered as micro or pico wind power generation. The range between about 100 kW and 500 kW and maybe even up to 1 MW is considered as medium-scale wind power generation and above 1MW is considered as utility scale. Small and medium scale wind generator systems have been around for a long time and significant growth is currently observed and predicted in this wind power segment, especially for rural and off-grid applications. However, very little research exists on small scale systems as compared to utility scale wind turbines, which justifies the inclusion of this wind power range in this study.

As mentioned, the toroidal winding is compared with both conventional overlap winding and non overlap winding generator topologies. To ease implementation of the different machine structures at the different power levels the winding layouts are kept as similar as possible in all cases. For the non overlap winding, the high winding factor 10/12 pole slot combination as also used in [16] is selected and a double layer winding layout is utilised. For the conventional three phase overlap winding three slots per pole is utilised throughout the design optimisation. Due to the solving times for the FE software increasing if the component count increases, a maximum of six slots per pole are utilised for the smaller wind generators and three slots per pole for the higher wind power levels, for the toroidal winding.

All of the wind generators considered in this study are optimised for minimum active mass (M_{Tot}) and minimum PM mass (M_{PM}), subject to certain design constraints as explained later in the paper. The design optimisation is done by means of the *Visual Doc* optimisation suite [17], which is coupled with static FE analysis to reduce simulation times. From the different optimisation algorithms available in *Visual Doc*, the gradient based, modified method of feasible direction (MMFD) is selected. This method is shown to consistently give the best results in the shortest amount of time for this particular study.

B. Design Specifications

As far as possible, in this study, reference designs for direct drive generators from literature are used for comparison. The design optimisation is done for the power levels of, 1 kW [18], 3 kW [19], 15 kW [14] and [16], 60 kW [15], 300 kW [20], 1 MW [15], 3 MW [3] and 7.5 MW [21]. Table I gives the design constraints for the different wind generator power levels considered.

For the smaller generators, more or less micro-scale, a minimum efficiency of 92 %, as is also specified in [19], is selected. For the small scale power range up to 60 kW an efficiency of $\eta_s > 94$ % is specified, which is the same as in [14]. For all the generators larger than 60 kW, it is specified that $\eta_s > 95$ %, which is mostly considered as a feasible value in literature for larger generators. The rated rotor speed (n_s), rated torque requirement and maximum allowable outer diameter (D_o) are found from the relevant reviewed literature works. The generator outer diameter is mostly determined by the turbine characteristics for smaller systems, because if the outer diameter becomes too large the

TABLE II. OPTIMISATION RESULTS VERSUS TURBINE POWER OF THE NON OVERLAP DOUBLE LAYER PMSGS.

	T_r, kNm	T_b, pu	$\Delta\tau_{NL}$, %	$\Delta\tau_L$, %	P_{ecs}, kW	P_{ecr}, kW	η_s, %	l, m	D_i, m	M_{PM}, kg	M_{Cu}, kg	M_{Fe}, kg	M_{Tot}, kg
1 kW	0.012	2.62	4.46	11.90	0.013	0.024	92.21	0.0195	0.205	0.36	2.73	4.03	7.12
3 kW	0.100	2.45	4.56	10.39	0.024	0.073	92.16	0.037	0.416	1.21	6.09	13.39	20.69
15 kW	1.001	2.06	2.20	2.80	0.144	0.102	94.29	0.105	0.511	7.79	18.90	58.17	84.86
60 kW	7.365	1.25	3.38	3.39	0.279	0.172	94.26	0.174	1.063	24.04	84.48	166.3	274.8
300 kW	67.24	1.31	1.24	4.41	1.157	1.739	95.34	0.290	2.591	129.6	269.9	934.5	1334
1 MW	332.9	1.19	0.47	1.73	3.776	2.939	95.38	0.420	3.237	461.9	632.4	2642	3736
3 MW	1927	1.46	0.97	2.06	7.402	5.767	95.47	1.300	4.770	1895	3018	8973	13885
7.5 MW	6156	1.2	0.57	2.35	10.09	37.71	95.25	0.740	11.67	4951	3515	19778	28244

TABLE III. OPTIMISATION RESULTS VERSUS TURBINE POWER OF THE CONVENTIONAL OVERLAP WINDING PMSGS.

	T_r, kN	T_b, pu	$\Delta\tau_{NL}$, %	$\Delta\tau_L$, %	P_{ecs}, kW	P_{ecr}, kW	η_s, %	l, m	D_i, m	M_{PM}, kg	M_{Cu}, kg	M_{Fe}, kg	M_{Tot}, kg
1 kW	0.012	4.25	19.26	39.97	0.024	0.011	92.04	0.028	0.1772	0.490	3.05	7.81	11.34
3 kW	0.101	2.03	8.85	18.34	0.041	0.013	92.29	0.045	0.3764	1.470	9.01	24.81	35.29
15 kW	0.992	3.11	13.37	31.52	0.182	0.036	94.01	0.1145	0.5232	7.820	25.22	60.77	93.91
60 kW	7.377	2.72	4.59	21.78	0.411	0.090	94.31	0.183	1.0728	29.54	76.02	162.1	267.7
300 kW	67.01	1.70	5.30	25.74	1.404	1.057	95.22	0.265	2.435	114.6	282.3	967.0	1364
1 MW	329.6	1.62	1.88	12.18	5.151	0.642	95.13	0.570	3.330	280.3	775.9	2117	3173
3 MW	1933	1.68	2.23	15.40	11.31	2.180	95.26	1.400	4.774	1338	3122	10302	14762
7.5 MW	6138	1.60	2.90	23.82	12.99	38.61	95.41	0.670	11.66	4120	3848	18427	26394

TABLE IV. OPTIMISATION RESULTS VERSUS TURBINE POWER OF THE TOROIDAL WINDING PMSGS.

	T_r, kN	T_b, pu	$\Delta\tau_{NL}$, %	$\Delta\tau_L$, %	P_{ecs}, kW	P_{ecr}, kW	η_s, %	l, m	D_i, m	M_{PM}, kg	M_{Cu}, kg	M_{Fe}, kg	M_{Tot}, kg
1 kW	0.012	6.53	17.17	37.47	0.026	0.011	92.21	0.025	0.184	0.69	1.50	5.770	7.96
3 kW	0.101	3.32	12.36	23.18	0.043	0.025	92.27	0.026	0.357	1.94	6.92	12.44	21.31
15 kW	0.993	4.4	2.35	4.93	0.165	0.01	94.00	0.08	0.512	6.49	21.04	45.22	71.43
60 kW	7.388	1.66	0.45	4.50	0.430	0.436	93.74	0.095	0.964	26.51	97.4	177.98	301.9
300 kW	67.04	1.29	3.36	8.46	1.216	1.368	95.02	0.160	2.358	105.6	277.5	773.9	1157
1 MW	330.1	1.34	1.05	2.54	3.81	0.61	95.04	0.283	3.353	305.3	674.5	1986	2966
3 MW	1844	1.36	1.59	6.00	9.19	2.16	95.30	0.637	4.810	1292	2983	7888	12197
7.5 MW	6161	1.24	1.8	13.2	10.81	23.71	95.01	0.425	11.748	3588	3078	18909	25574

TABLE I. DESIGN SPECIFICATIONS AT THE DIFFERENT WIND POWER LEVELS CONSIDERED.

	T_r (kNm)	T_b (pu)	η_s (%)	n_s (r/min)	p	f_s (Hz)	D_o (m)
1.00 kW	0.012	2.0	92	800	10	67	0.3
3.00 kW	0.13	2.0	92	300	20	50	0.510
15.0 kW	1.0	2.0	94	150	40	50	0.655
60.0 kW	7.35	1.1-1.5	94	78	60	39	1.2
300 kW	67	1.1-1.5	95	50	70	29	2.5
1.00 MW	330	1.1-1.5	95	29	160	39	3.5
3.00 MW	1910	1.1-1.5	95	15	160	20	5.0
7.50 MW	6120	1.1-1.5	95	12	160	16	12

generator structure interferes with the aerodynamic properties of the wind turbine. For larger systems, factors such as manufacturing constraints, transportation, installation and other logistical factors largely influence the outer diameter. Fig. 3 shows the maximum allowable outer diameter versus wind generator power rating. It is clear from Fig. 3 that as the generator power increases, the increase in D_o is increasingly more constrained.

Due to the higher rotational speed, the number of poles (p) selected for the smaller systems cannot be too high as the electrical frequency (f_s) will be too high, which will significantly increase the frequency dependent losses of the generator. For the utility scale generators p is kept constant to ease implementation of the models. Other aspects include ease of manufacturing and segmentation

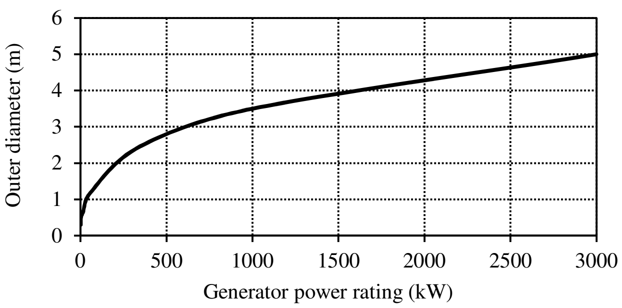

Fig. 3. Maximum generator outer diameter versus turbine power rating.

especially for larger generators. Furthermore, important in the design of PM generators is the load torque ripple and especially the no-load cogging torque as explained in [16]. In [22] it is specified that the cogging torque of direct drive PM wind generators should be at least in the range of 1.5 - 2 %. In some cases it is specified as low as 0.5 %. However, for comparison purposes as also done in [14] a no load cogging torque value of $\Delta\tau_{NL} < 2$ % is chosen and a load torque ripple value of $\Delta\tau_L < 4$ %.

Most of the smaller wind turbine systems make use of passive yawing, fixed pitch, passive furling for high wind speed protection, and electromagnetic braking. It is found from previous practical iterations as explained in [23] that the maximum breakdown torque (T_b) of the generator should be specified as at least $T_b > 2$ pu. For systems larger than 50 kW, which utilise variable pitch and other forms of braking, the maximum torque of the generator is usually in the range $1.1 < T_b < 1.5$ pu as also explained in [23]. The average rated torque at rated wind speed (T_r) is used as the base value in all cases. The machine design parameters, indicated by **[X]**, to be optimised for the different PMSG topologies, as well as the output performance parameters indicated by **[Y]** are given as

$$\mathbf{X} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} = \begin{bmatrix} l \\ h_c \\ h_m \\ h_{ry} \\ h_{sy} \\ \sigma_w \\ \sigma_m \end{bmatrix}; \quad \mathbf{Y} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \\ y_6 \\ y_7 \end{bmatrix} = \begin{bmatrix} M_{Tot} \\ M_{PM} \\ T_r \\ T_b \\ \Delta\tau_{NL} \\ \Delta\tau_L \\ \eta_s \end{bmatrix}. \quad (1)$$

In (1) l indicates the machine active length, h_c the slot conductor height, h_{ry} and h_{sy} the rotor and stator yoke heights respectively, σ_w the slot width to average slot pitch ratio, and σ_m the magnet pitch to pole pitch ratio. For the toroidal winding PM machine, h_{sy} gives the height of the common stator yoke. In this case h_m, h_{ry} and σ_m consist of two components, for the top and bottom PM rotors respectively. Furthermore, in this case, to ease manufacturing, h_c and σ_w are taken as the same for the top and bottom slots.

IV. Optimisation Results

Tables II and III give the optimisation results versus turbine power rating for the non overlap and conventional overlap winding direct drive PMSGs. Table IV gives the optimisation results for the new concept toroidal winding PMSG. Fig. 4 shows the active mass required per kW versus wind turbine power rating and Fig. 5 shows the PM mass per kW required. When observing Figs. 4 and 5 it is seen that especially regarding the PM content, the toroidal winding PMSG performs much more poorly than the other topologies at the micro wind power level ($<$ 3 kW). At this power level the non overlap winding performs the best. From about 15 kW it is observed that the toroidal winding generator performs much better. The reason for the poorer performance of the toroidal winding at the low power levels, is the increase in turbine speed and, thus, decrease in pole number as given in Table I. Due to the increase in yoke heights with a decrease in pole count the end-windings of the toroidal winding become much longer, which decreases its performance. Furthermore, the inner PM rotor is also placed at a much less optimum airgap diameter.

From the higher medium scale range and upwards to utility scale, it is observed that the performance of the non overlap winding starts to deteriorate when compared to the other generator topologies, especially regarding PM content. It is known that the torque performance of the non overlap windings are not as good as that of the conventional overlap winding topologies. This is also indicated in Tables III and IV by observing the maximum value of T_b achieved by the overlap and toroidal winding generator topologies. Thus, as shown in Fig. 3, the outer diameter gets much more constraint for the higher wind power levels with the torque requirement significantly higher. The wind generator, thus, needs to develop much more torque from a very limited torque diameter, which is the reason for the poorer performance of the non overlap winding topology.

The non overlap winding generator is shown to consistently comply the closest with the limits set for $\Delta\tau_{NL}$ and $\Delta\tau_L$, with the conventional overlap winding yielding the highest torque ripple in most cases. At the lower power levels it becomes increasingly more difficult for all of the topologies to adequately minimise the torque ripple. More elaborate torque ripple minimisation techniques as described in [16] and commonly used classical torque ripple reduction methods such as for instance skewing, can be employed in this case. It is also shown that it is possible to reduce the torque ripple of the toroidal winding generator to within acceptable limits. For the smaller generators, the possibility also exists to increase the number of slots per pole, which eases the reduction of the torque ripple as shown in Fig. 10. The PM rotor losses P_{ecr} for the non overlap winding PMSG are shown to be considerably higher than those of the overlap winding and especially the toroidal winding PMSGs, even though the PMs are segmented in the analysis. Fig. 6 shows the ratio of the maximum allowable outer diameter to the generator axial stack length, which is also known as the aspect ratio. It is clear that the toroidal winding has a much shorter axial length than the other topologies, which should make manufacturing easier. Some of the other parameters given in Tables II, III and IV include the stator core losses (P_{ecs}), generator inside diameter (D_i), and the conductor and steel mass (M_{Cu} and M_{Fe}). The no load losses, of which the magnitude will dictate the efficiency of the generator at low load values are given by $P_{NL} = P_{ecs} + P_{ecr} + P_{wf}$. The wind and friction losses indicated by P_{wf} will be more or less similar for all of the different topologies.

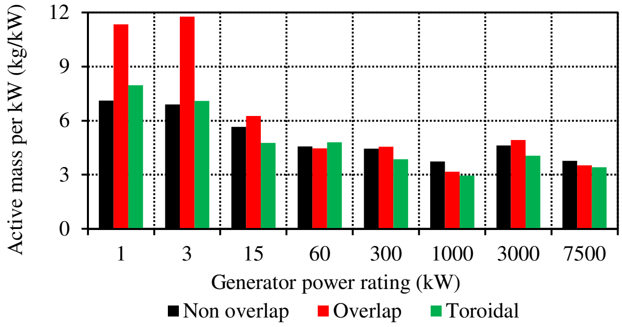

Fig. 4. Ratio of active mass per kW versus wind turbine power rating.

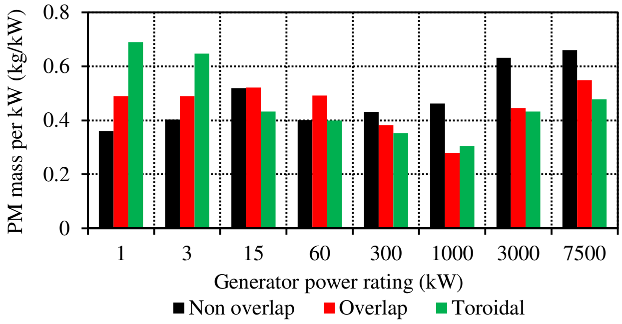

Fig. 5. Ratio of PM mass per kW versus wind turbine power rating.

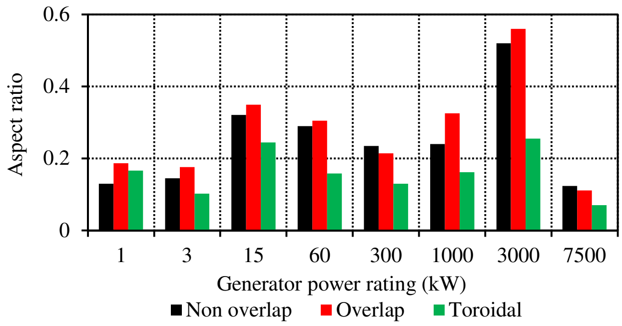

Fig. 6. Ratio of generator outer diameter to axial stack length versus wind turbine power rating.

V. Further Toroidal Winding Aspects

Although the focus in this study is mainly on the electromagnetic analysis of the toroidal winding PMSG, several additional observations are made in the evaluation of this concept as explained in this section.

A. General Observations

Due to the manner in which the toroidal winding stator is wound, it is possible to obtain a very good fill factor, and solid conductors can be used. However, in this case eddy-current losses in the conductors become a concern. If foil type conductors are used, the conductors will normally be stacked as in Fig. 7(a). However, for the toroidal winding as is proposed in this paper, the conductors are stacked as in Fig. 7(b). Fig. 8 shows the effect the placement of the conductors has on the eddy-current losses in the generator. It is clearly shown that if the conductors are segmented as in Fig. 7(a) almost no change in the eddy-current losses is observed and very high conductor eddy-current losses can be expected. However, by segmenting the conductors as in Fig. 7(b) as for the toroidal winding, a significant reduction in the eddy-current losses is observed. The toroidal winding PMSG, thus, has a major advantage in this regard.

In the case of PM generators, to limit the PM losses the PMs are usually segmented. However, as shown in Fig. 9, which indicates the PM rotor losses versus magnet segments, P_{ecr} for the toroidal winding PMSG is very low, even if solid magnets are employed. The non overlap winding generator on the other hand has much higher PM losses even when segmented. Thus, solid magnets and solid rotor back yokes can easily be utilised for the toroidal winding PMSG without any additional losses.

Fig. 10 shows the magnitude of $\Delta\tau_{NL}$ versus the number of slots per pole. It is clear that $\Delta\tau_{NL}$ decreases with an increase in the number of slots per pole. Due to the way the toroidal winding is wound, it is easier to accommodate more stator slots as opposed to conventional overlap windings, which means that the torque ripple can be reduced more easily. With the use of two PM rotor components the two rotors can also be offset from one another to reduce the equivalent torque ripple magnitude as shown in Fig. 13. Care should, however, be taken in the design optimisation so that the difference is not too high in the different torque ripple harmonic components of the two PM rotors.

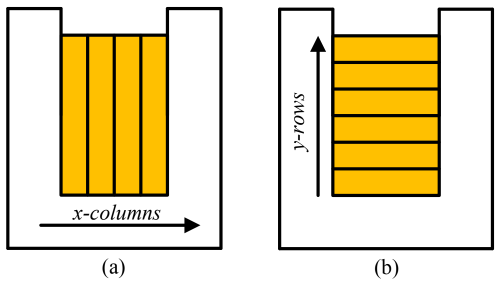

Fig. 7. (a) Conductors segmented in the horizontal (x) direction and (b) vertical (y) direction.

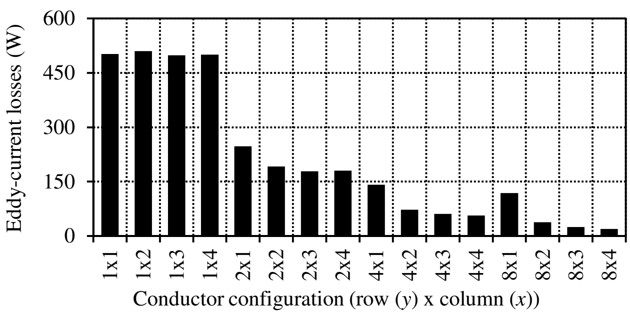

Fig. 8. Conductor eddy-current loss versus conductor configuration for the prototype toroidal winding PMSG.

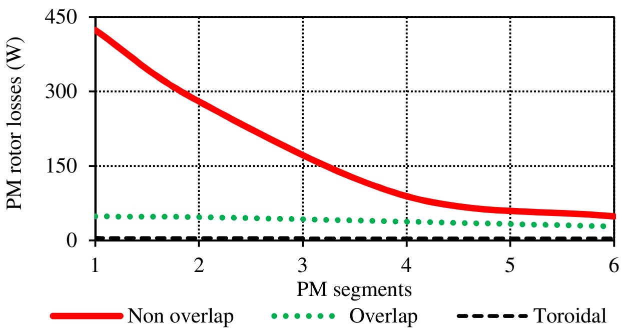

Fig. 9. PM rotor loss versus PM segments for the optimum designed non overlap, conventional overlap and prototype toroidal winding PMSGs.

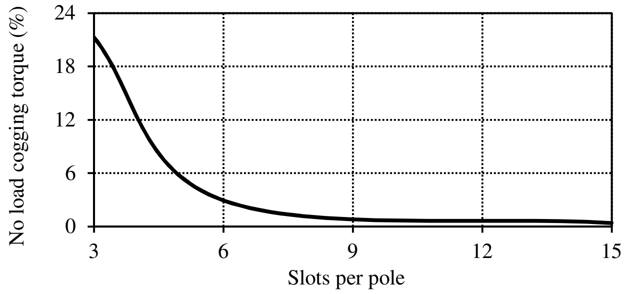

Fig. 10. No load cogging torque of the optimum 15 kW toroidal winding PMSG versus number of slots per pole.

B. Summary of Advantages and Disadvantages

The main advantages and disadvantages of the toroidal winding PMSG can be summarised as below. It should, however, be noted that many aspects of the toroidal winding PMSG still require further investigation, before these aspects can be adequately commented on.

- Much shorter end-windings than conventional overlap windings, especially for higher pole numbers.
- Easy segmentation due to no coil overlapping.
- Much better torque performance compared to non overlap winding PMSGs.
- Higher fill factors can be achieved more easily.
- Placement of conductors allows for easier mitigation of conductor eddy-current losses.
- Low PM rotor losses, which means that solid yokes and PMs can be considered.
- Much better torque ripple characteristics compared to conventional overlap winding topologies.
- Shorter stack length.
- Although more comment is required from industry, the windings seem relatively easy to manufacture.
- Not suited for high speed applications with low pole numbers, due to the increase in common stator yoke height and also coupling between the two PM rotors.
- Manufacturing, especially regarding the placement and fixing of the stator is still a question.
- Heat dissipation might be a problem for high current density applications, due to the stator winding being placed between the two PM rotors.

VI. Performance Results

For the prototype performance evaluation, only the toroidal winding PMSG is evaluated. The performance of the non overlap winding PMSG is evaluated more thoroughly in [14]. The manufacturing of a conventional overlap winding PMSG is not considered as this type of machine has been evaluated in numerous other studies in literature.

A. Prototype Generator

The prototype toroidal winding PMSG is manufactured by modifying the double rotor, non overlap winding PMSG of [10] and as shown in Fig. 2(b). Due to the modification of an existing machine structure it should be noted that the prototype toroidal winding machine is not an optimum design and this quick modification is merely used to verify the operational principles of this machine type. As in [10] the stator is divided into eight sections and is manufactured by moulding each stator section in epoxy resin. These stator sections are fixed to a stator mounting plate and inserted between the two PM-rotors. Fig. 11(a) shows an experimental toroidal winding stator section making use of

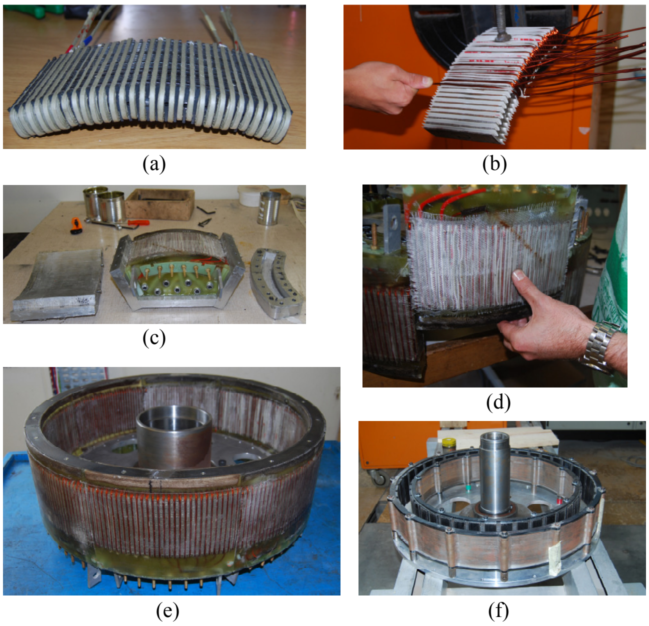

Fig. 11. (a) Manufactured toroidal test winding section with rectangular wire, (b) toroidal winding section being wound, (c) winding section in mould, (d) moulded winding section being shifted into position, (e) completed toroidal winding stator and (f) PM rotor.

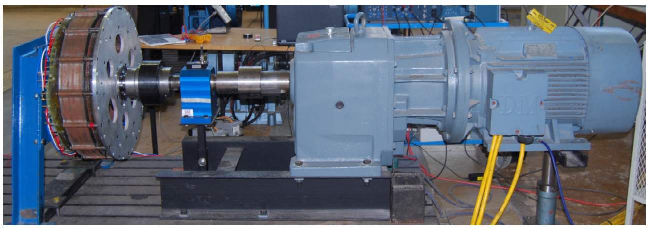

Fig. 12. Prototype toroidal winding PMSG mounted on the test bench in the laboratory.

rectangular wire and Fig. 11(b) shows the toroidal winding stator section being wound. Fig. 11(c) shows a toroidal winding stator section inside the mould and (d) shows a stator section being shifted into position. Figs. 11(e) and (f) show the completed toroidal winding stator and PM rotor respectively. The prototype generator on the test bench in the laboratory is shown in Fig. 12.

B. Performance Evaluation

Fig. 13 shows the FE predicted no load cogging torque, and load torque ripple at rated load. The no load torque developed by both the bottom and top PM rotor parts are shown in Fig. 13. During manufacturing the PMs of the two PM rotor parts can be offset by a skewing angle corresponding to one slot pitch. As seen in Fig. 13 the torque ripple is not completely removed, due to the torque ripple waveforms of the top and bottom PM rotor parts not

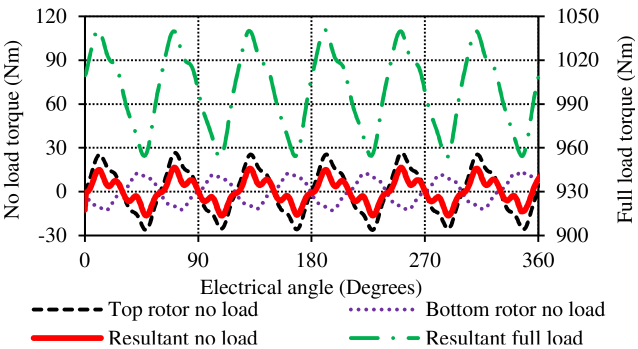

Fig. 13. FE predicted no-load cogging torque and load torque ripple of the 15 kW toroidal winding PMSG prototype.

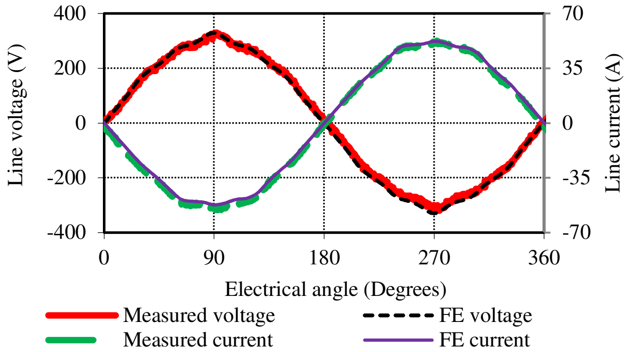

Fig. 14. FE predicted and measured open circuit line voltage and line current at rated load versus electrical angle of the toroidal winding PMSG.

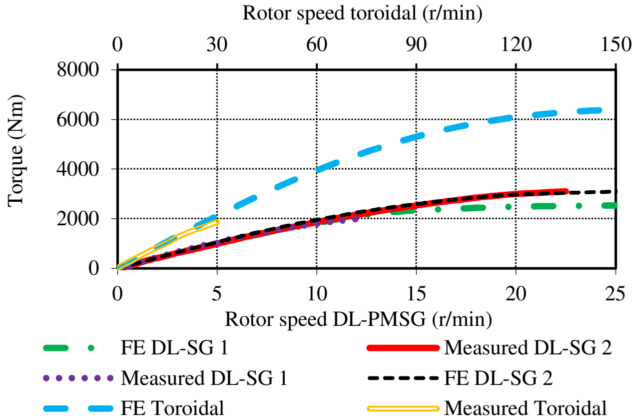

Fig. 15. FE predicted and measured braking (short-circuit) torque profiles of the non overlap PMSGs of Fig. 2(a) (DL-SG 1) and Fig. 2(b) (DL-SG 2) and the toroidal winding PMSG of Fig. 2(c).

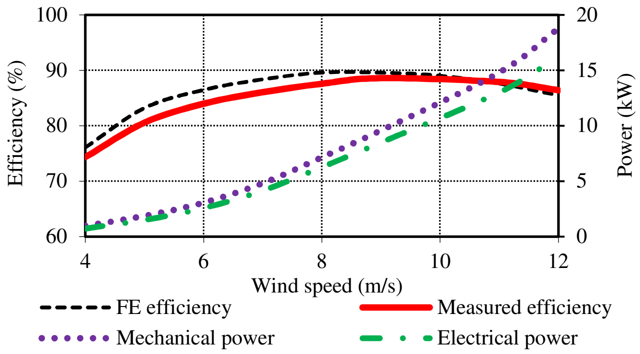

Fig. 16. FE predicted and measured efficiency, as well as the measured mechanical input and electrical output power versus wind speed of the toroidal winding PMSG.

matching. There are also different harmonic components in the two waveforms. Thus, it is important in the minimisation of the torque ripple of the toroidal winding PMSG during optimisation that the different frequency components in the two waveforms match as closely as possible.

Fig. 14 shows the open circuit induced voltage waveform and the line current at rated load of the toroidal winding PMSG. In order to give an indication on the torque performance of the toroidal winding PMSG Fig. 15 shows the short-circuit torque versus speed performance of the prototype toroidal winding, non overlap double layer PMSG as evaluated in [14] and the double rotor non overlap winding PMSG before modification and as evaluated in [10]. Clearly the toroidal winding PMSG is shown to achieve a much higher maximum torque. The mechanical input power and electrical output power, as well as the measured and FE predicted efficiency of the toroidal winding PMSG are shown in Fig. 16. The reason for the difference between the measured and FE predicted efficiencies at low wind speeds is due to the incorrect prediction of the frequency dependent no load losses. Due to wind generators operating in the partial load region most of the time it is important that the no load losses are estimated correctly and kept as low as possible in the design optimisation.

VII. Conclusion

In this paper the new concept toroidal winding PMSG is shown to perform well regarding active mass and especially PM content for a wide range of wind turbine powers. Only at the very small and micro power levels is the toroidal winding PMSG shown not to be a suitable option, with this machine type not suited for low pole number applications. It performs better than conventional overlap winding PMSGs due to the much shorter end-windings of this generator. At the small and micro power level the non overlap winding PMSG should be the most suitable option. Even at the lower medium scale this generator could still be an option due to its favourable characteristics regarding torque ripple and ease of manufacturing. However, at the utility scale level the amount of PM material required by the non overlap winding increases significantly as compared to the other generator topologies. Although the performance of the toroidal winding PMSG is not that much different from that of the overlap winding PMSG at the utility scale power level, there are several other favourable characteristics of the toroidal winding PMSG to consider. These are e.g. easier reduction of torque ripple, easier segmentation and reduced conductor eddy currents and PM losses. There are, however, several aspects of the toroidal winding PMSG which need to be investigated further, such as structural and thermal analysis as well as some further study on the manufacturing processes to employ for this type of generator. In this study the focus was merely to provide an electromagnetic analysis regarding the applicability of the toroidal winding PMSG over the whole wind turbine power range. With the electromagnetic characteristics known and the operating principles of the toroidal winding PMSG validated by means of the manufactured prototype, future studies can now focus more on the implementation of this generator type.

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VIII. Biographies

Johannes H. J. Potgieter (S'10) received the B.Eng. degree in electrical and electronic engineering in 2008 and the M.Sc. (Eng.) and the Ph.D. (Eng.) degrees in electrical engineering from the University of Stellenbosch, Stellenbosch, South Africa in 2011 and 2014 respectively. As of May 2014 he is employed as a post-doctoral research assistant at the University of Oxford, Oxford, United Kingdom. His research interests include wind power generation technologies, automotive drive train solutions and the design and optimisation of permanent magnet and switched reluctance electrical machines.

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