# Permanent Magnet Excitation of a Two and Four Pole Pair Dual Wound Machine

J Frederick Eastham[1], Boyuan Yin[1], Xanwu Zeng[1], Christopher Hodge[2] and Xiaoze Pei[1]
1 University of Bath, UK
2 BMT Defence & Security, Bath UK

**Synopsis**

The practicality of implementing, and the advantages that can arise from, a Dual Wound Machine (two segregated windings on one generator driven by a single prime mover) have been previously reported. It has been demonstrated that two separate machines mounted in a common frame offer no advantages over a standard tandem arrangement and the presence of two sets of end windings in the central area imposes volumetric overheads. By comparison Dual Windings offer a more compact arrangement with no volume overheads. This paper considers the use of permanent magnets to provide the required 2 and 4 pole excitation fields for a generator with dual two and four pole windings. Electrical and magnetic isolation is desirable in both sets of windings; electrical isolation is relatively straight-forward but magnetic isolation is more complex. Magnetic isolation is gained by ensuring that the two windings' MMF have no space harmonics in common, including the fundamentals, using techniques established in the earlier papers. The use of a permanent magnet excitation system is considered where the basic concept is to arrange the magnets in two radially separated layers in the normal way, but where the magnets are of opposing polarity they are removed completely. The harmonic analysis of the resulting field is established using an analytical technique and this is corroborated through two-dimensional finite element flux analysis, which is also used to establish the machine performance.

Keywords: Dual Windings; Permanent Magnet; Excitation

## 1. Introduction

Traditional ship design employs direct drive mechanical propulsion and separate generators to provide electrical ships services. In the latter half of the twentieth century electric propulsion emerged as the most efficient arrangement for several vessel types [Hansen 2015], [Doerry 2015], and the number of electrically propelled ships has grown rapidly over the ensuing years. Compared with direct-drive diesel systems, electric propulsion removes the direct mechanical coupling between the prime mover and propeller and has great potential to reduce fuel consumption, enhance dynamic performance and increase the system reliability. Integrated full electric propulsion (IFEP), combines the electrical propulsion and ships services networks so that no generator is slightly loaded even when propulsion load is low. As summary of the advantages of IFEP is:

1. The arrangement of engines on the ship becomes more flexible because the connection between the diesel machines and the propulsion is eliminated.
2. All engines providing electrical power helps to decrease the total number of engines, which contributes to the reduction of the weight and volume for the ship, as well as the noise and vibration.
3. Independent engine groups and propulsion machines can use more commercial solutions for maintenance and to decrease capital costs.

IFEP is difficult to fit in smaller vessels leading to a wish to reduce the volume of the overall system in order to spread the benefits of electrification more widely. One possibility is to merge the propulsion and ships service generators into one machine for which one possibility is to use a dual wound machine.

## 2. Dual wound generators

A dual wound machine provides power for both ship services and the propulsion segment from a single generator, but electrical and magnetic isolation of the two power system segments is retained and, because a dual wound machine only requires one prime mover, the overall volume if the system is reduced, and importantly for a warship the overall prime mover and generator length is reduced. This has been previously considered by the authors [Hodge 2012 & 2015]-[Eastham 2014].

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**Authors' Biographies**

**J Frederick Eastham DSc Dr.h.c.** is now an Emeritus Professor at Bath University after being Head of Department, Dean and Pro-Vice-Chancellor there. He is a fellow of the Royal Academy of Engineering and the Royal Society of Edinburgh. He is a consultant to a number of manufacturing companies.

**Boyuan Yin** received B.Eng. from the North China Electric Power University in Beijing, China and the University of Bath in the UK in 2018. He is currently under the third year Ph.D. study in the University of Bath. His research field is hybrid DC circuit breaker and electric machine design.

**Xianwu Zeng** received his MSc and PhD at the University of Manchester between 2009 and 2014. In 2019, he joined the University of Bath as a Lecturer. His principal research interests include power electronics, motor drives, hybrid electric vehicles, and renewable energy interface systems.

**Christopher Hodge** is the Chief Electrical Engineer at Defence and security, BMT, he is a Fellow of the Royal Academy of Engineering, received the OBE in 2015 for services to RN Engineering and is an Honorary Fellow of the IMarEST.

**Xiaoze Pei1** received her Ph.D. degree from the University of Manchester in 2012. She joined the University of Bath as a Lecturer in 2017 and became a Reader (Associate Professor) in 2022. Her research interests include electrical power applications of superconductivity, hybrid DC circuit breaker and electric machine design.

The two outputs of the dual wound machine are developed from two separate windings on the stator which share the same slots. The key aspect of the design is that the stator winding arrangement must eliminate the electromagnetic coupling between the two windings to avoid cross-coupling between the supplies. In addition, in the wound rotor case each of the two rotor windings should couple magnetically only with the stator winding for which it is intended. However, in the case of permanent magnet excitation, in common with all permanent magnet machines, it is not possible to control the permanent magnet field and the machine has constant excitation for both pole numbers. The different stator winding strategies that can be applied to dual wound machines are described in [Hodge 2012 & 2015] [Eastham 2014] [Yin 2021] which also describe the harmonics analysis and the same methods are used in this paper.

## 3. Aim

The purpose of this paper is to extend the previous work by considering the permanent magnets to excite the machine dual windings.

## 4. The Dual Wound Machine

A nominal design was conceived based on an existing machine at the University of Bath to allow assessment of the machine itself and its excitation. The dimensions are given in Table 1. The new dual winding has two separate two-layer stator windings (four layers in total) one having two pole pairs the other four. This can be considered as either a machine in its own right or as a sector of a machine having greater pole numbers, for example, a four and eight pole arrangement.

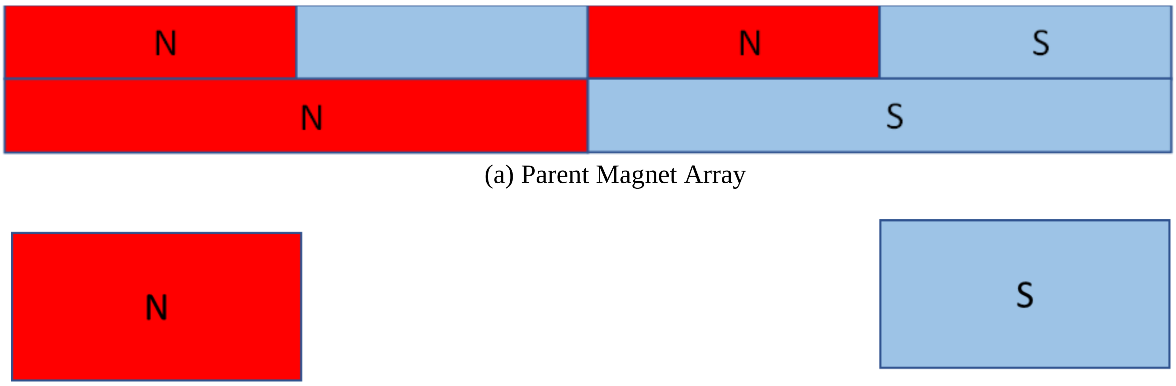
Table 1: Machine Dimensions

| | Stator | Rotor |
|---|---|---|
| Number of slots | 36 | 24 |
| Diameter | 190.5 mm | 186.5 mm |
| Axial length | 123.6 mm | 139.5 mm |
| Slot opening | 2.7 mm | 3.5 mm |
| Airgap | 2 mm | |
| Stator outer diameter | 295 mm | |

### 4.1. *Permanent magnet excitation design*

One possible solution for the excitation magnet arrangement is to simply include sets of magnets for each pole number as shown in Figure 1(a) however in this arrangement sections of the periphery which contain magnets of opposing polarity will provide little or no magnetic field in the airgap and can therefore be omitted as shown in in Figure 1(b). This “Resultant Magnet” array can be formed not only for the 2 and 4 pole case but for any pair of excitation poles.

### 4.2. *Resultant Magnet System:*



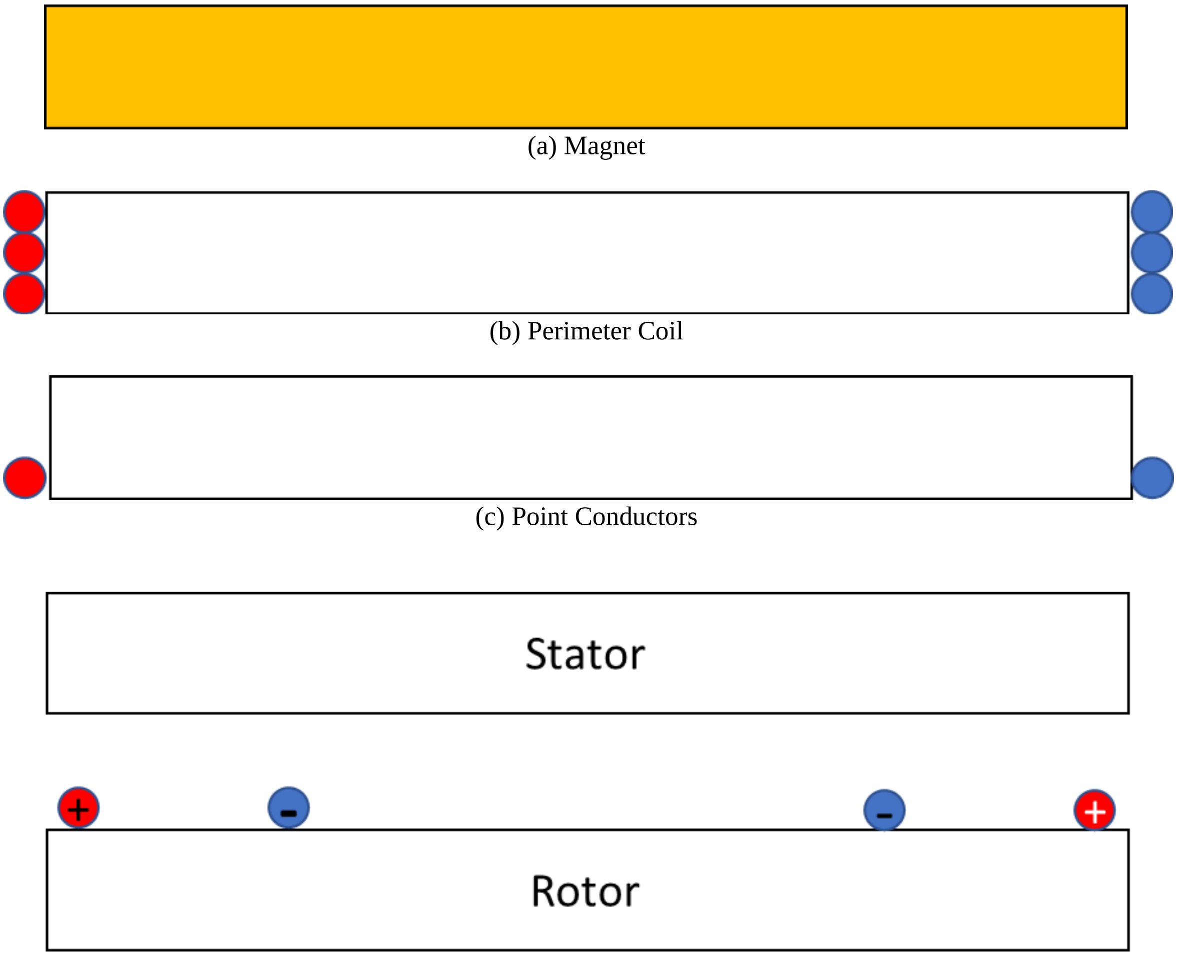

(a) Parent Magnet Array

(b) Equivalent Array to (a)

Figure 1: Derivation of the resultant magnet system

*4.3. Coil and conductor representation of permanent magnets:*

A commonly accepted way of calculating the field from a permanent magnet, figure 1(a), often used in FEA, is to replace the magnet by a perimeter coil as shown in 2D in Fig 2b. If the perimeter coil can be replaced by a point coil as shown in Fig 2c then the form of algebraic analysis used to find the harmonics described in [Eastham 2010] can be used.




(a) Magnet

(b) Perimeter Coil

(c) Point Conductors

(d) Finite Element model

Figure 2: Conductor Representation of Magnets and Arrangement for Finite Element Model

To check the accuracy of the point coil approach three simple FEA models were used of the same general dimensions as the target machines, modelling the magnet, the perimeter coil, and the point coils. Each perimeter coil side and point conductor carries a current of LmHc where Lm is the magnet depth and Hc is the magnet coercivity

The model for the point coil case is shown in Figure 2(d), the chosen configuration is the 2 and 4 pole array using the equivalent magnets shown in Fig. 1b. The resulting fields along a line at the centre of the air gap between the upper steel block and the magnets are shown at Figure 3.

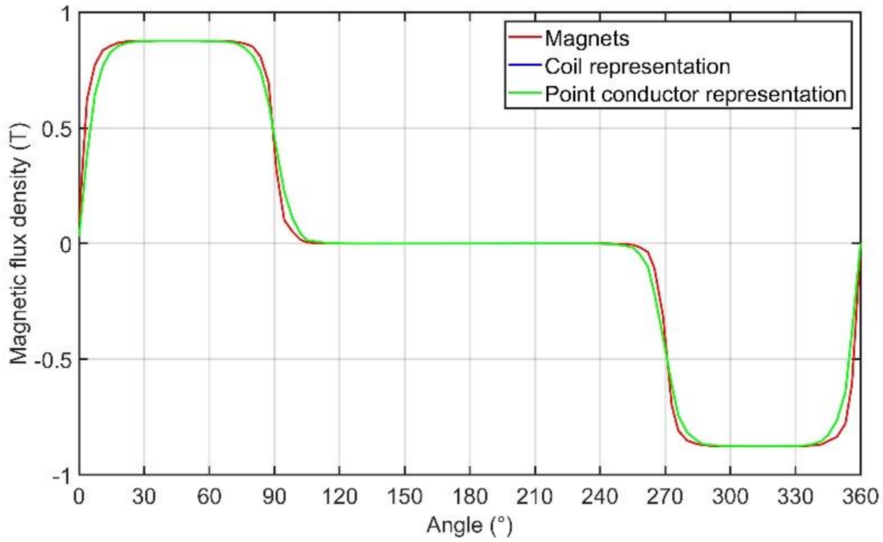


Figure 3:FEA comparison between magnet representations

It can be observed from the results that the magnet and perimeter coil representation are identical and that the point conductor representation yields an adequate representation of the magnet field. It can therefore be used to find the harmonic amplitudes.

### *4.4. Analysis of the field from the magnets:*

In the permanent magnet dual wound generator, the excitation fields for both pole numbers are present at all times and in common with all permanent magnet machines it follows that the generated voltages are also present at all times and cannot be controlled. Therefore, the purpose of calculating the rotor harmonic fields in the permanent magnet case is to ensure that the output waveshapes meet the design requirements. There are two factors that can be used to control the magnitude of the harmonic induced voltages namely the coil pitch of the stator windings and the pitch of the rotor magnets. This later factor can be analysed using the point conductor approach using the diagram of Figure 4.

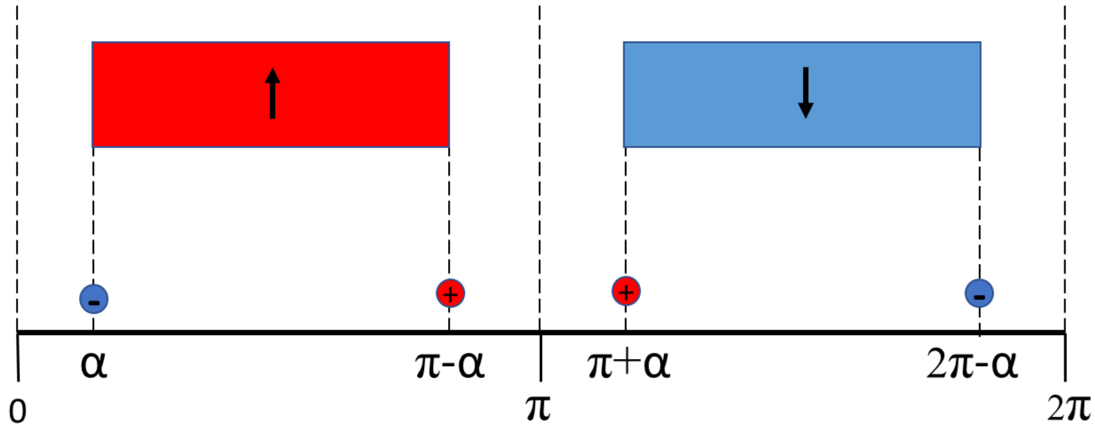



Figure 4: Point conductor representation of short pitched magnets

Each point conductor carries a current of LmHc where Lm is the magnet depth and Hc is the magnet coercivity. As shown in Appendix 1 the Electric loading for the pth harmonic in Amps /radian is given by:

$$J_{mp} = \frac{2H_c L_m}{\pi}\cos(p\alpha)$$

The important harmonics that can induce line voltages in the stator windings are the 5th an 7th and the design can concentrate on reducing them. For the two-pole case, as shown in figure 4, to cancel the 5th harmonic put α=

π/10 then cos (pα) = 0 and to cancel the 7th put α= π/14 then cos (pα) = 0 For the four-pole case; with the pole pitch and magnet pitch one half that in the 2-pole case equivalent results to the ones above are obtained; when α=π/20 the 10th harmonic is cancelled, when α=π/28 the 14th harmonic is cancelled. The magnet pitches can therefore be chosen to cancel either of the two excitation harmonics. The stator winding design can then be adjusted to minimise the other. For this reference design it was chosen to cancel the 7th harmonic excitation field then the equivalent array is developed as shown in figure 5.

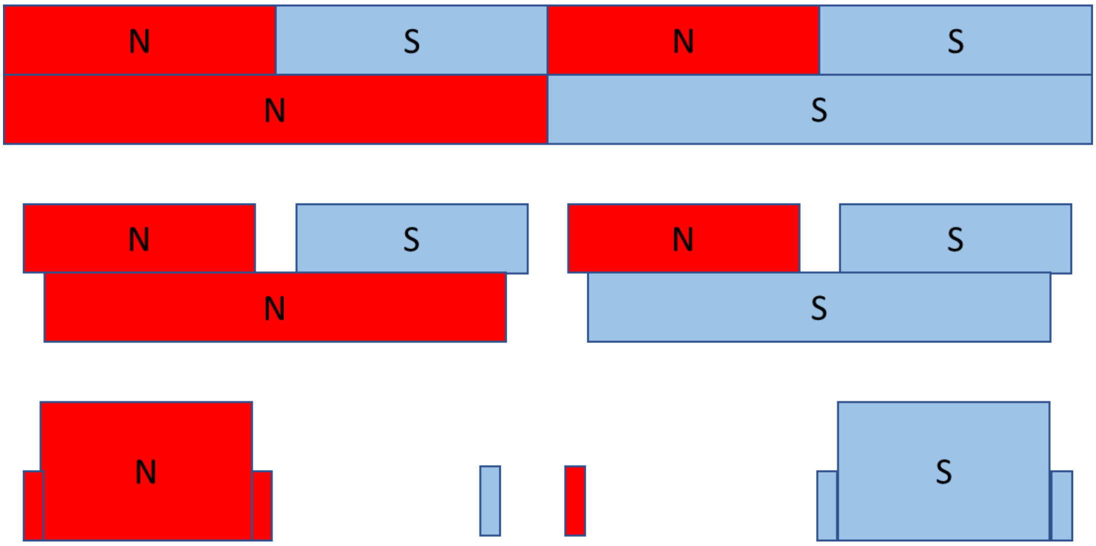
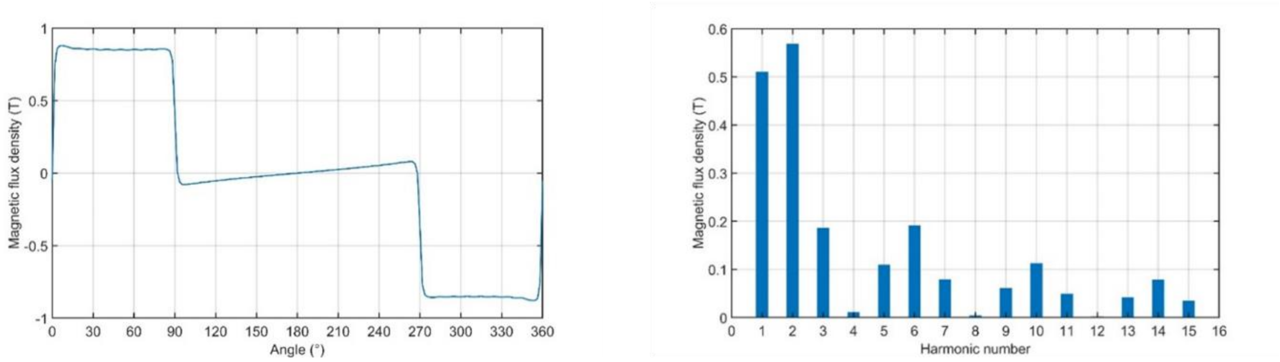



Figure 5: Equivalent array for the short-pitched magnet

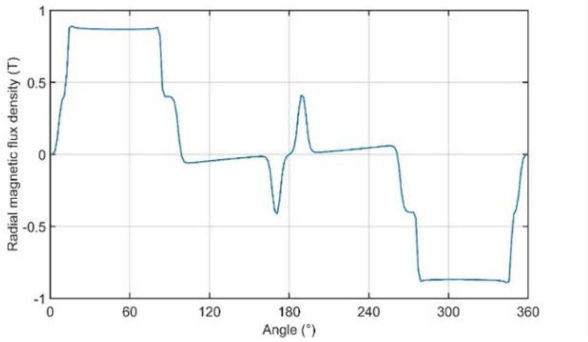
### *4.5. Confirmation of the field produced by the magnets*

Using the FEA model shown in figure 9 the airgap fields produced by both fully pitched and short pitched magnets were modelled. The results are shown in figures 6 and 7 and it can be seen that the 7th and 14th harmonics present in the fully pitched case have been cancelled when the magnets are short pitched.

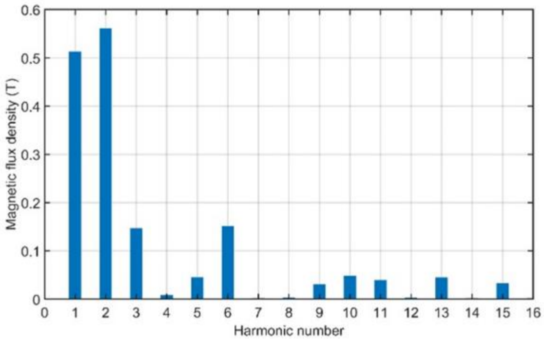



(a) airgap magnetic field distribution (b) airgap magnetic field harmonics

Figure 6: Full pitch magnet machine



(a) airgap magnetic field distribution



(b) airgap magnetic field harmonics

Figure 7: Short-pitched magnet machine

## 5. Design of the stator windings

### *5.1. Winding Layout*

The stator windings produce induced emf from the magnetic flux density provided by the rotor windings. The frequency of the output voltage is proportional to pole number, so the 4-pole winding produces 2 times the frequency of the 2-pole winding. The 2-pole and 4-pole windings share the same 36 slots on the stator frame as shown in Fig. 8, each pole winding is a conventional double layer winding with the 2-pole using 6 slots per pole and phase and the 4-pole three. The coil pitch is 14 slots for the 2-pole and 7 slots for the 4-pole. These pitch values reduce the 10-pole induced voltage in the 2-pole winding case and the 20-pole in the 4-pole case. Since the 7th harmonic is cancelled in the excitation field it cannot induce stator voltages and the harmonic content of the line voltages should be of reasonable amplitude.

| Slot | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 Pole | R | R | R | R | R | R | -B | -B | -B | -B | -B | -B | Y | Y | Y | Y | Y | Y | -R | -R | -R | -R | -R | -R | B | B | B | B | B | B | -Y | -Y | -Y | -Y | -Y | -Y |
| | R | R | -B | -B | -B | -B | -B | -B | Y | Y | Y | Y | Y | Y | -R | -R | -R | -R | -R | -R | B | B | B | B | B | B | -Y | -Y | -Y | -Y | -Y | -Y | R | R | R | R |
| 4 Pole | R | R | R | -B | -B | -B | Y | Y | Y | -R | -R | -R | B | B | B | -Y | -Y | -Y | R | R | R | -B | -B | -B | Y | Y | Y | -R | -R | -R | B | B | B | -Y | -Y | -Y |
| | R | -B | -B | -B | Y | Y | Y | -R | -R | -R | B | B | B | -Y | -Y | -Y | R | R | R | -B | -B | -B | Y | Y | Y | -R | -R | -R | B | B | B | -Y | -Y | -Y | R | R |

Figure 8: Stator winding distribution

The dual wound machine is expected to generate independent supplies. The flux density can only couple with the windings that have the same pole number. At the same time, the current in a winding can only produce fluxes corresponding to its winding harmonics. It therefore follows that to avoid electromagnetic coupling between the windings there should be no common winding harmonics

Table 2 and Table 3 show the winding harmonics of the 2-pole stator winding and the 4-pole stator winding. It can be seen that there are no common harmonics between the two windings, fulfilling the condition for no mutual coupling and ensuring that the two outputs are independent. The calculations are performed using the method given in [Eastham 2014] in which the windings are represented by harmonic, equivalent, positive negative and zero winding sequence sets which when supplied with 3 phase currents produce forward backward and stationary fields. However, if the currents are balanced the fields produced by the zero sequence sets are zero. The excitation waves from the rotor all travel in the forward direction and they produce balanced forward sequence voltages in the positive sequence sets and balanced negative sequence voltages in the negative sequence sets. The voltages produced in the zero sequence sets are all in phase and, for example, in a star connected system will appear in the phase voltages but not in the line.

Table 2: 2-pole Stator Winding Harmonic

| Harmonics | PPS | NPS | ZPS |
|---|---|---|---|
| 1 | 0.90 | 0.00 | 0.00 |
| 3 | 0.00 | 0.00 | 0.32 |
| 5 | 0.00 | 0.03 | 0.00 |
| 7 | 0.11 | 0.00 | 0.00 |
| 9 | 0.00 | 0.00 | 0.24 |
| 11 | 0.00 | 0.08 | 0.00 |
| 13 | 0.02 | 0.00 | 0.00 |
| 15 | 0.00 | 0.00 | 0.09 |
| 17 | 0.00 | 0.08 | 0.00 |
| 19 | 0.08 | 0.00 | 0.00 |
| 21 | 0.00 | 0.00 | 0.09 |

Table 3: 4-pole Stator Winding Harmonics

| Harmonics | PPS | NPS | ZPS |
|---|---|---|---|
| 2 | 0.90 | 0 | 0 |
| 6 | 0 | 0 | 0.33 |
| 10 | 0 | 0.03 | 0 |
| 14 | 0.013 | 0 | 0 |
| 18 | 0 | 0 | 0.33 |
| 22 | 0 | 0.013 | 0 |
| | | | |

PPS – Positive phase sequence
NPS – Negative phase sequence
ZPS – Zero phase sequence

## 6. Simulation of the complete machine using 2D finite element models

A non-linear 2D finite element simulation using COMSOL has been performed to verify the above results for both the airgap fluxes considered by the harmonic analysis and the slot leakage fluxes. Figure 9 shows the 2D model and Figure 10 the flux density levels in the stator and rotor cores and teeth; these are in the normal range for this type of machine. The end winding resistance and reactances are not considered in this paper (requiring a 3D model) but may be included in future work. Figures 11 to 15 Show the induced voltages in the machine windings for various conditions; the machine used the "equivalent magnet array" of figure 5. Figure 11 shows the open circuit induced voltage results for the two-pole winding, at (c) the line and phase voltages are compared and it can be seen that the line voltage is less distorted. This is due to the third harmonic zero phase sequence induced voltages being cancelled by the connection. Comparable results for the loaded condition appear in (d) and the smoothing effect due to the stator impedances can be seen. Figure12 gives the same results as Figure 11 but for the 4-pole winding.

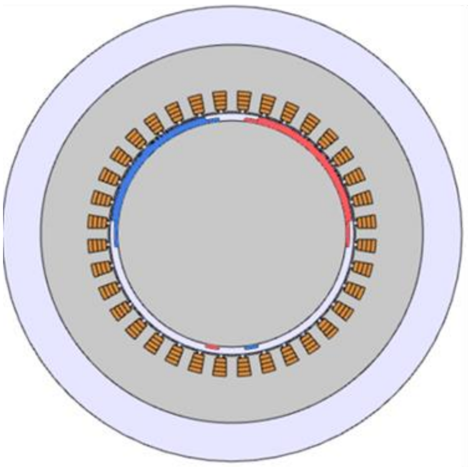


Figure 9: 2D Finite Element Model

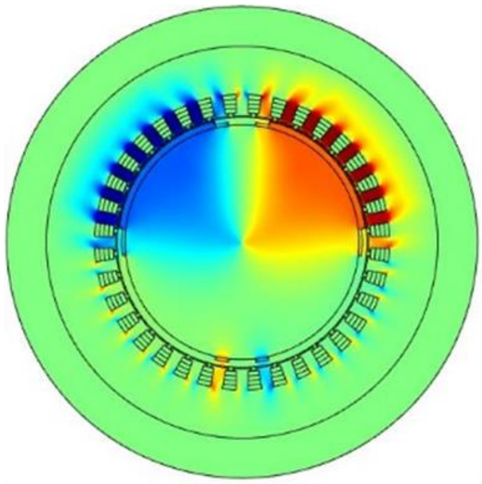
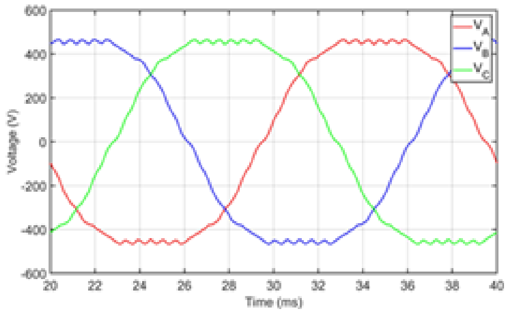
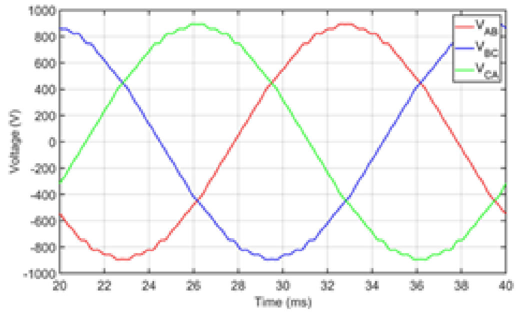


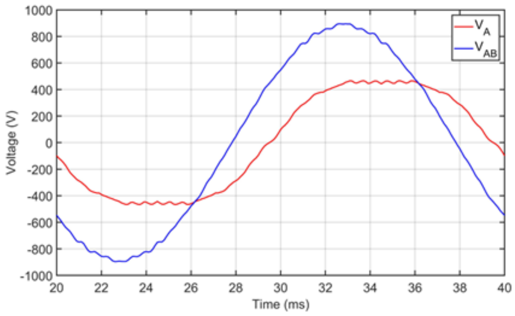
Figure 10: Flux Distribution



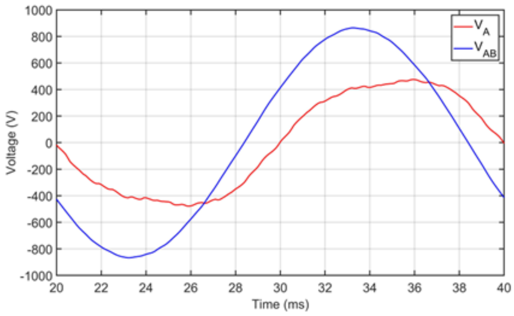

(a) 2 pole 3 phase no-load voltage




(b) 2 pole 3 phase no-load line voltage

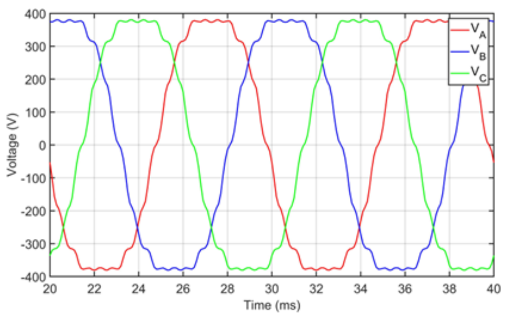



(c) 2 pole no load phase and line voltage

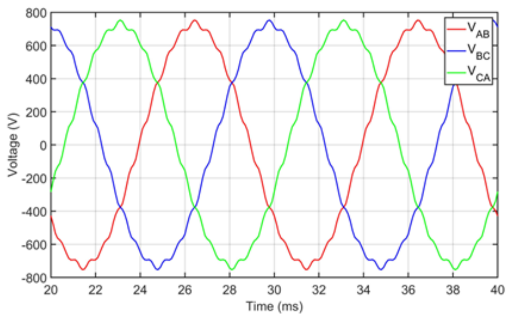



(d) 2 pole full load phase and line voltage

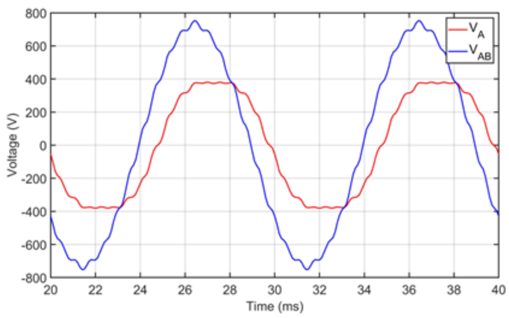
Figure 11: Short-pitched magnet machine simulation results



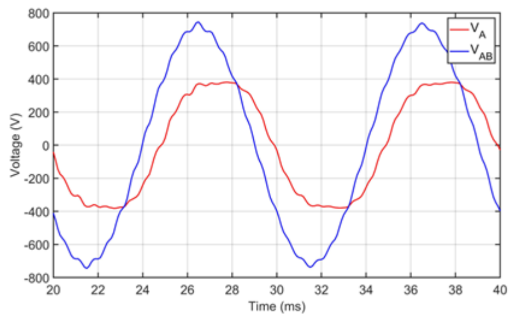

(a) 4 pole 3 phase no-load voltage




(b) 4 pole 3 phase no-load line voltage

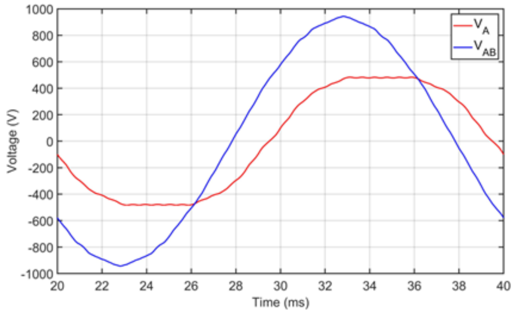



(c) 4 pole no-load phase and line voltage

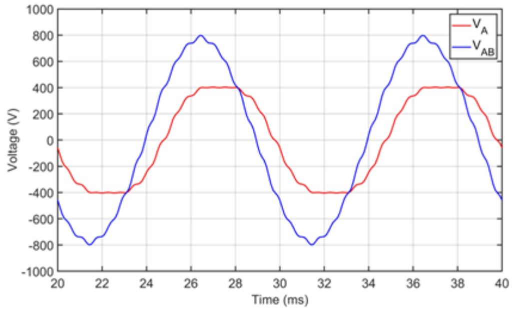



(d) 4 pole full load phase and line voltage

Figure 12: Short-pitched magnet machine simulation results:



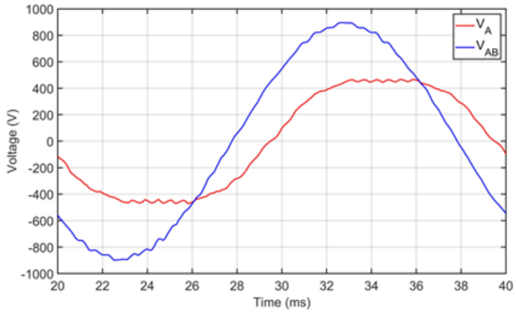

(a) 2 pole phase and line voltage with only 2 pole magnets



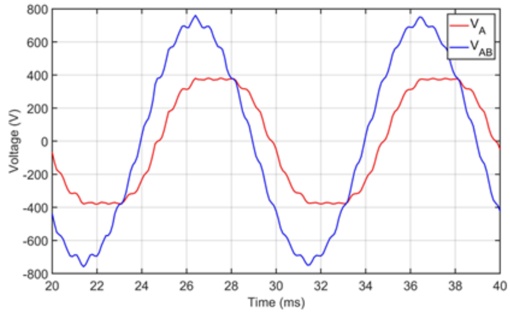

(b) 4 pole phase and line voltage with only 4 pole magnets.

Figure 13: Short-pitched magnet machine simulation results:

Figure 13 draws a comparison between machines using a conventional short pitched magnet and those using the equivalent magnet system and it can be seen that Figure 13 (a) gives identical results to Figure 11(c) whilst Figure 13(b)gives identical results to Figure 12(d). This confirms that the equivalent magnet system produces the same flux distribution as the parent configuration.



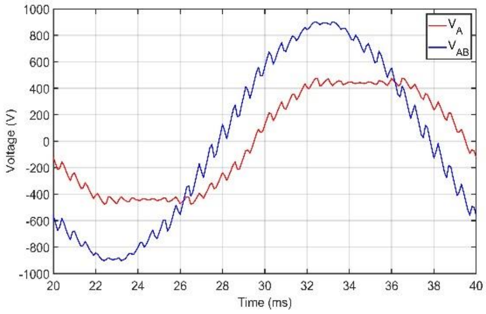

(a) open circuit 2 pole phase and line voltage when 4 pole output is at full load



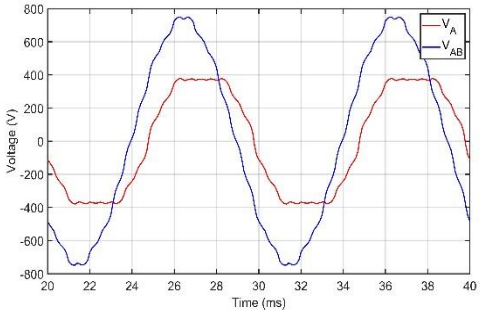

(b) open circuit 4 pole phase and line voltage when 2 pole output is at full load

Figure 14: Short-pitched magnet machine simulation results:

The results of Figure 14 are included to check the coupling between the stator windings and indicate as expected that there is no coupling. When the 4-pole winding carries current the open circuit 2-pole voltage at (a) is identical to the open circuit voltage at Figure 11(c). Similarly, the open circuit voltage at Figure 14(b) is the same as the voltage at Figure 12(c).




(a) 2 pole phase and line voltage




(b) 4 pole phase and line voltage

Figure 15: Full pitch magnet machine simulation results

Figure 15 indicates the affect of the short-pitched magnets; the waveforms for fully pitched magnets are considerably more distorted than when short pitched magnets are used.

## 7. Conclusions

The outline design of a reference dual winding generator using permanent magnet excitation has been presented. The machine is based on using 2 and 4 pole stator windings and can be regarded as a machine using these pole numbers or a sector of a machine using multiples of the numbers, for example 4 and 8 poles.

A novel magnet system using less magnetic material is developed from a parent conventional magnet system having two layers each carrying one of the wanted pole numbers. It is termed “A resultant magnet system” and shown to operate identically to the parent configuration whilst using less magnetic material.

In common with all permanent magnet machines the two outputs cannot be controlled but it is shown that the dual windings are not coupled so that the output of one winding is not affected by load current in the second.

It is demonstrated that the harmonic content of the output voltages can be controlled by both the rotor magnet pitch and the pitch of the windings. In this particular design the harmonic content of the line voltages has been of particular concern but it will be appreciated that using the methods given in the paper other outcomes are possible for example the third harmonic content of the phase voltages could be removed at the expense of the fundamental amplitude by a suitable magnet pitch.

**References**


J. F. Hansen and F. Wendt, “History and state of the art in commercial electric ship propulsion, integrated power systems, and future trends,” *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2229-2242, Dec. 2015.

N. Doerry, J. Amy and C. Krolick, “History and the status of electric ship propulsion, integrated power systems, and future trends in the U.S. navy,” Proceedings of the IEEE, vol. 103, no. 12, pp. 2243-2251, Dec. 2015.

C. G. Hodge, J. F. Eastham and A. C. Smith, “The harmonics analysis of machine excitation,” Int. Naval Engineering Conf. (INEC), Edinburgh, May. 2012.

J. F. Eastham and C. G. Hodge “The harmonics analysis of machine phase windings,” Int. Naval Engineering Conf. (INEC), Glasgow, May. 2014.

C. G. Hodge and J. F. Eastham, “Dual wound machines for electric ship power systems,” IEEE Electric Ship Technologies Symposium (ESTS), Alexandria, VA, 2015, pp. 62-67.

B. Yin, X. Pei, X. Zeng, J. F. Eastham, C.G. Hodge, O. Simmonds, Design and analysis of dual wound machine for electric ships” International Conference on Electrical Machines 23rd-26th August 2020, Gothenburg.

## Appendix

The point conductors each carry a current of $H_C L_m$, or in the more general case there are $S$ current positioned at $\theta_S$ the electric loading on the $p_{th}$ harmonic is:

$$J_{mp} = \frac{1}{\pi} \sum_{s=1}^{s=S} H_c L_m \, e^{-jp\theta_s}$$

Then for the currents shown in Figure 4:

$$J_{mp} = \frac{H_c L_m}{\pi} \left[ e^{-jp\alpha} - e^{-jp(\pi-\alpha)} - e^{-jp(\pi+\alpha)} + e^{-jp(2\pi-\alpha)} \right]$$

$$J_{mp} = \frac{2H_c L_m}{\pi} \left[ e^{-jp\alpha} + e^{jp\alpha)} \right]$$

$$J_{mp} = \frac{2H_c L_m}{\pi} \cos{(p\alpha)}$$