Magnetic Decoupling of Winding Design in Dual Wound Generators

Boyuan Yin, Xiaoze Pei, John Frederic Eastham, Han Wang, Chris Hodge, Oliver Simmonds, Christopher Vagg, Xianwu Zeng

Abstract—A general shipboard power system contains multiple electrical machine sets to provide electrical power with different ratings for both the propulsion system and the ship service. In order to achieve the most compact design and maximize the weight reduction, a study of using a single dual wound generator to replace the electrical machine sets is presented in this paper. It consists of dual two-layer windings of different pole numbers which use the same slots and share one prime mover, producing two independent power supplies. This paper verifies a dual wound machine designed for no electromagnetic coupling by algebraically analyzing the spatial harmonic magnetic field distribution. Further verification of the absence of electromagnetic coupling due to both the airgap and slot leakage fluxes is provided by 2D finite element modeling. The dual wound generator prototype using the principle is designed, built and experimentally tested. The experimental results match well with the simulation results, validating the independence of the two power outputs and showing that the winding end-turns also do not couple. The results are significant for applications where multiple independent power supplies are needed, or where an auxiliary power supply is needed which could be drawn from an existing traction motor.

Index Terms—Dual wound machine, Electric ship, Harmonic decoupling, Independent power supplies.

I. INTRODUCTION

Traditional large cruise ships and naval warships contain a set of diesel generators for ship service systems, and another separate set of prime movers for propulsion systems [1]-[2]. This direct-drive diesel system can occupy a large space on the ships with low power efficiency. Electric propulsion has emerged to be the most efficient arrangement for several vessel types [3]-[4], and the number of electrically propelled ships has grown rapidly over the last ten years [5]. Compared with direct-drive diesel systems, electric propulsion systems have great potential to reduce fuel consumption, enhance dynamic performance and increase the system reliability [6]-[8]. Integrated full electric propulsion (IFEP) systems remove the direct mechanical coupling between the prime mover and propeller, building an all-electric network, which can provide power for both the ship services and the propulsion [9]. All the engines in IFEP systems are used to generate electrical power, rather than to provide mechanical propulsion, so the total number of engines can be reduced, which contributes to the reduction of the weight and volume for the ship, as well as noise and vibration. IFEP systems can also achieve more flexible ship engine arrangements by eliminating the mechanical connections between the diesel generators and the propulsion. The independent engine groups and propulsion machines provide more flexible commercial solutions for maintenance and thus reduce the capital costs. In summary, the IFEP systems can provide significant benefits for the ship structures. The primary purpose of a dual wound generator is to supply different subsystems with only one compact machine. Compared with the general IFEP system, a dual wound machine only needs one prime mover, which takes less volume and mass than two separate prime movers to achieve the same total power rating, saving space on the ship [10]. With only one electric machine, there are no integration problems between the generators.

Dual wound generators are shown to have great potential to provide better power quality [11], better torque quality [12] and reduced losses [13]. The different winding strategies that can be applied to dual wound machines are described in references [11], [14]. Some studies of the dual wound machine generators have been performed in [15]-[16] using the same winding pole numbers and therefore being magnetically coupled. However, in these machines the change of operation condition of one output would fully impact the operation of the other [15]-[16]. Based on the principle of the IFEP system, this paper is based on the design of a dual wound generator having the novel feature that each winding uses a different pole number, providing the electric power for both the propulsion and ship services simultaneously without any electromagnetic coupling [17]-[18]. The two outputs of the dual wound generator are from two windings on the stator, which mechanically share the same slots but can be windings of different forms. The proposed stator winding arrangements have the benefit of virtually eliminating the electromagnetic coupling between them to avoid cross-coupling between the power supplies. In addition, each of the two rotor windings needed should couple with only the stator winding for which it is designed. By developing a dual wound generator prototype, it is possible to experimentally investigate if the windings are coupled and this paper designs a prototype 2-pole and 6-pole dual wound generator operating at 1500 rpm based on an existing machine frame. An analytical

Boyuan Yin, Xiaoze Pei and Fred Eastham are with the Dept. of Electronics & Electrical Engineering, University of Bath, United Kingdom. (e-mail: B.Yin@bath.ac.uk, X.Pei@bath.ac.uk, jfeastham@aol.com)

Han Wang, Christopher Vagg and Xianwu Zeng are with the Dept. of Mechanical Engineering, University of Bath, United Kingdom. (e-mail: xz2478@bath.ac.uk)

Chris Hodge and Oliver Simmonds are with the BMT Defence & Security UK Ltd.
harmonic calculation based on the airgap fields is presented showing that there is no electromagnetic coupling between the two stator windings. A harmonics analysis using the algebraic method and analytical equations developed in [19]-[21] is used in this paper. A 2D finite element model has been used for simulation in COMSOL to demonstrate the magnetic flux density distribution and the dynamic performance. The detailed simulation results are published in a previous research paper [18] to show that there is no coupling due to both the airgap fields and the slot leakage flux. The designed dual wound machine is experimentally tested in this paper and the results further verify that there is no electromagnetic coupling between the two outputs from the two sets of stator windings; this not only includes the airgap and stator slot leakage fields but importantly also the end-winding fields which have not been considered previously.

The structure of this paper is as follows. Section II introduces the dual wound generator topology and design based on the existing machine frame, including the rotor winding distributions and the magnetic flux density in the air gap; Section III presents the stator electromagnetic decoupling performance and the winding harmonic analysis; Section IV presents the operation of the dual wound generator with resistive load using COMSOL finite element modelling. Section V demonstrates the experimental results compared with the simulation results and further validates the independence of the two power outputs. Section VI discusses the system aspects and the potential applications of the dual wound generator.

II. GENERATOR DESIGN AND AIR GAP FLUX DENSITY

A. Dual Wound Generator Topology

The prototype dual wound generator designed in this paper is a synchronous machine with a separately excited wound rotor using the existing machine frame. Table I presents its key dimensions.

<table>
<thead>
<tr>
<th>Item</th>
<th>Stator</th>
<th>Rotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of slots</td>
<td>36</td>
<td>24</td>
</tr>
<tr>
<td>Diameter</td>
<td>190.5 mm</td>
<td>186.5 mm</td>
</tr>
<tr>
<td>Axial length</td>
<td>123.6 mm</td>
<td>139.5 mm</td>
</tr>
<tr>
<td>Slot opening</td>
<td>2.7 mm</td>
<td>3.5 mm</td>
</tr>
<tr>
<td>Airgap</td>
<td>2 mm</td>
<td></td>
</tr>
<tr>
<td>Stator outer diameter</td>
<td>295 mm</td>
<td></td>
</tr>
</tbody>
</table>

The stator has 36 slots and the rotor 24. To achieve a sinusoidal form of airgap magnetic field, the rotor windings use concentrically distributed windings. Based on the slot dimensions, the total number of turns of the 2-pole rotor is 1100 and the 6-pole rotor has the total number of turns of 1000. The design provides maximum airgap flux density without saturation in the frame structures. Considering the maximum exciting current and the packing factors, the wire used for the rotor is SWG 27 with a diameter of 0.4166 mm. The 2-pole and 6-pole rotor windings are excited through four slip rings and brushes. The 2-pole stator has 20 turns in each slot, and the 6-pole stator has 12 turns. Considering the slot packing area and the rated current, the 2-pole stator uses SWG 21 wire and the 6-pole stator uses SWG 19 wire.

B. Air Gap Flux Density Produced by the Rotor Windings

The machine operating performance highly depends on the air gap flux density distribution generated by the rotor windings. In this dual wound generator design, concentric windings are used to produce a good approximation to a sinusoidal magnetic field in the airgap. Due to the different number of conductors in each slot, the rotor winding can generate a good approximation to the sine wave air gap flux density required if the slot conductors are themselves sinusoidally distributed. It will be appreciated that the number of slots in a wavelength is finite and, in the case of the 6-pole winding, small. However, even in this case, careful design can lead to a reasonably sinusoidal air gap field.

The rotor machine frame has 24 slots. The 2-pole winding has a pole pitch of 12 slots while the 6-pole winding has 4. The coil distributions are shown in Fig. 1, which shows the 2-pole distribution (one coil set out of two) in Fig. 1(a) and the six-pole distribution (one coil set out of six) in Fig. 1(b). Each of these coil sequences is repeated with arrows showing the current directions.

![Fig. 1. Rotor winding diagram](image)

For a single general machine winding which consists of a group of coils in a series connection, the conductor distribution can be expressed as a Fourier expansion as shown below in equation (1).
\[ n = \sum_{p=1}^{\infty} N_p \cos(p\theta + \varphi_p) \]  

The slot configuration can be replaced by a thin patch of current the width of the slot opening on an iron surface, then if a general slot at \( \theta_s \) contains \( N_s \) conductors and has a slot opening of \( 2\delta \) the conductor distribution produced by the slot is given by equation (2).

\[ \overline{N}_p = \frac{1}{\pi} \int_{\theta_{s} - \delta}^{\theta_{s} + \delta} N_s e^{-ip\theta_s} \frac{\sin p\delta}{p\delta} \, \text{d} \theta \]  

(2)

If the assumption of point conductors is made then

\[ \frac{\sin p\delta}{p\delta} \to 1 \quad \text{as} \quad \delta \to 0 \]  

(4)

\[ \overline{N}_p = \frac{1}{\pi} N_s e^{-ip\theta_s} \]  

(5)

Assuming that the winding has \( S \) slots and there are \( N_s \) conductors in the general \( sth \) slot, then the winding distributions are given by equation (6)

\[ \overline{N}_p = \frac{1}{\pi} \sum_{s=1}^{S} N_s e^{-jp\theta_s} = N_p e^{j\Phi_s} \]  

(6)

The rotor windings of the dual winded machine use concentrically distributed windings as shown in Fig. 1. The harmonics distribution can be calculated using equation (6).

The magnetic field harmonic distribution of the 2-pole and 6-pole rotor windings are calculated and presented in Table II and Table III based on equation (6), with the harmonics ranged from the fundamental up to the 35th harmonic. It clearly indicates that there is no common harmonic field between the two windings, which means there is no mutual electromagnetic coupling between them due to the air-gap flux. This is important since it implies that during the transient change of the field current in one winding, there will be no back-emf induced in the other winding.

### Table II 2-pole Rotor Magnetic Field Harmonics Distribution

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>Magnetic field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.603</td>
</tr>
<tr>
<td>23</td>
<td>0.026</td>
</tr>
<tr>
<td>25</td>
<td>0.024</td>
</tr>
</tbody>
</table>

### Table III 6-pole Rotor Magnetic Field Harmonics Distribution

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>Magnetic field (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.536</td>
</tr>
<tr>
<td>21</td>
<td>0.077</td>
</tr>
<tr>
<td>27</td>
<td>0.060</td>
</tr>
</tbody>
</table>

Fig. 2 shows the 2D FEA simulation results of the magnetic field distribution around the airgap with rotor excitation current of 1 A. The approximate sinusoidal magnetic field is the result of the combination of the square waves generated by each rotor coil. The 2-pole rotor magnetic field in the air gap (Fig. 2(a)) better approximates a sinusoid than the 6-pole rotor winding (Fig. 2(b)) because the 2-pole winding has more slots per pole. The peak magnetic field for 2-pole and 6-pole are similar, and around 0.5 T, because the total number of turns are almost the same. The ripples appearing on the magnetic flux density along the airgap are because of the slopping.

The two rotor winding distributions can start from any phase position with respect to each other. The best position can be taken as that which produces the smallest peak magnetic field when both rotor windings are excited and a simulation has been done to change the relative position between the two windings by one slot at a time. Fig. 3 shows the total field at the best position when the 2-pole and 6-pole windings are aligned, i.e. where the 2-pole and the 6-pole windings start in the same slot. The following finite element modelling results presented in this paper are based on this aligned rotor winding distribution.
III. WINDING HARMONICS & ELECTRO-MAGNETIC COUPLING

The stator windings generate induced emf from the airgap magnetic field produced by the rotor windings. The frequency of the output voltage is proportional to the pole number. The 6-pole winding produces a frequency that is 3 times higher than that produced by the 2-pole winding. The stator machine frame has 36 slots, for which the 2-pole and 6-pole stator winding distribution is as shown in Fig. 4. Each pole winding is distributed in two layers, where the 2-pole stator windings are above the 6-pole stator windings, thus there are four layers in total. This design aims to maximize the induced voltage and minimize the spatial harmonics from the windings whilst ensuring that there is no electromagnetic coupling between them. The 2-pole and 6-pole windings are both short-pitched: the 2-pole has a pitch angle of 120° and the 6-pole has 150°. Two terminals for each phase (R, Y and B) are connected to a terminal panel so that the load can be connected to each phase.

It is worth noting that since the 2-pole and 6-pole fields rotate at the same speed as the rotor, the relative position between the airgap fluxes of the 2-pole and 6-pole windings, which depends on the power factor of the loads, remains fixed. The stator windings therefore use the same aligned position as the rotor windings assuming that the load power factor is the same. Further study could be done if the load power factors are known for the two loads.

The dual wound generator is designed to provide two independent power supplies. The 2-pole rotor windings can only produce 2-pole magnetic fluxes that couple with the 2-pole stator windings. The 6-pole rotor windings can only generate 6-pole magnetic flux that couples with the 6-pole stator windings. At the same time, the current in a winding can only produce fluxes corresponding to its winding harmonics. This ensures that there is no electromagnetic coupling between the 2-pole and 6-pole windings, so that there are no common winding harmonics.

Phase ‘R’ of a general machine winding which consists of a group of coils each of N turns connected in series gives a conductor distribution for the pth harmonic of:

\[ \bar{N}_{pR} = \frac{1}{\pi} \sum_{s=1}^{s=S} N_{sR} e^{-j\theta_{sR}} = N_{pR} e^{-j\theta_{pR}} \]  

Similarly, the conductor distribution for the ‘B’ phase is shown in equation (8) and ‘Y’ phase is shown in equation (9).

\[ \bar{N}_{pB} = N_{pB} e^{-j\theta_{pB}} \]  
\[ \bar{N}_{pY} = N_{pY} e^{-j\theta_{pY}} \]

The three-phase stator windings of the dual wound machine use the double layer distributed winding as shown in Fig. 4. The top layer formed by the leading coil sides has 6, π/3 length phase bands. The bottom layer formed by the second coil sides is reverse repeat of the top layer displaced by α π. The angle between the m coil sides in a phase band for the general case is π/3m. The conductor distribution on the pth harmonic for the R phase top layer taking both phase bands is shown in equation (10).

\[ \bar{N}_{pRT} = \frac{N}{\pi} \sum_{k=0}^{k=m-1} e^{-j\pi k \frac{\alpha_p}{3}} - e^{-j\pi (k \frac{\alpha_p}{3} + 1)} \]  

where m is the number of coils per phase band.
If p is an even number, then:
\[ \bar{N}_{pRT} = 0 \]
If p is an odd number, then:
\[ \bar{N}_{pRT} = \frac{2N}{\pi} \sum_{k=0}^{k=m-1} e^{-j\pi k \frac{\alpha_p}{3}} \]

Hence the conductor distribution can be written as equation (13).

\[ \bar{N}_{pRT} = \frac{2N}{\pi} \left[ \frac{1 - e^{-j\pi \frac{\alpha_p}{3}}}{1 - e^{-j\pi \frac{\alpha_p}{3}}} \right] = \frac{2N}{\pi} \left[ e^{-j\pi (\frac{m-1}{6})} \sin \left( \frac{m \pi}{3} \right) \sin \left( \frac{m \pi}{6} \right) \right] \]

Since the bottom layer is a reverse repeat of the top displaced by απ (α is the coil short-pitched angle) the R phase winding conductor distribution is as shown in equation (14).

\[ \bar{N}_{pR} = \bar{N}_{pRT} (1 - e^{-j\alpha_p} \sin \frac{\alpha_p}{2}) \]  

hence
\[ |N_{pR}| = \frac{4N}{\pi} \left[ \frac{\sin \left( \frac{m \pi}{3} \right) \sin \left( \frac{m \pi}{6} \right)}{\sin \left( \frac{m \pi}{6} \right)} \right] \]

In this formula, m times the expression \( \frac{\sin \left( \frac{m \pi}{6} \right)}{\sin \left( \frac{m \pi}{6} \right)} \) is called the distribution factor and the expression \( \sin \left( \frac{m \pi}{6} \right) \) is the pitch or chording factor. The conductor distribution for the red phase can be written as

\[ \bar{N}_{pR} = N_p \]

Then since the winding is symmetrical the conductor distribution for the blue phase is as shown in equation (17) and the yellow phase is as shown in equation (18).

\[ \bar{N}_{pB} = N_p e^{-j\frac{2\alpha_p}{3}} \]  
\[ \bar{N}_{pY} = N_p e^{j\frac{2\alpha_p}{3}} \]

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

The positive sequence \( n_{fp} = N_p \) if \( p = 1, 7, 13 \ldots \) and is zero...
The winding harmonic distributions of the 2-pole and 6-pole stator windings are shown in Table IV and Table V. The winding harmonics are separately calculated into three components: the positive phase sequence (PPS), negative phase sequence (NPS) and zero phase sequence (ZPS). When the windings are supplied by 3-phase currents, the three phase sequences can correspondingly produce forward, backward and stationary fields. Table IV and Table V show that there is no common harmonic term appearing between the 2-pole and 6-pole stator windings, which verifies that there is no electromagnetic coupling between them due to the airgap field. From the results shown in Table II and Table V, there is also no common harmonic component between the 2-pole rotor winding and 6-pole stator winding. Similarly, examining Table III and Table IV it is apparent that the 6-pole rotor windings have no mutual harmonics with the 2-pole stator windings. The harmonics analysis therefore shows that the rotor windings only couple with their corresponding stator winding.

<table>
<thead>
<tr>
<th>Harmonics</th>
<th>PPS</th>
<th>NPS</th>
<th>ZPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.83</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>0.00</td>
<td>0.17</td>
<td>0.00</td>
</tr>
<tr>
<td>7</td>
<td>0.13</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>11</td>
<td>0.00</td>
<td>0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>13</td>
<td>0.08</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>17</td>
<td>0.00</td>
<td>0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>19</td>
<td>0.07</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>23</td>
<td>0.00</td>
<td>0.08</td>
<td>0.00</td>
</tr>
<tr>
<td>25</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>29</td>
<td>0.00</td>
<td>0.13</td>
<td>0.00</td>
</tr>
<tr>
<td>31</td>
<td>0.17</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>35</td>
<td>0.00</td>
<td>0.83</td>
<td>0.00</td>
</tr>
</tbody>
</table>

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

IV. MODELLING OF PERFORMANCE

A. Rotor Excitation under No-Load Condition

A non-linear 2D finite element simulation using COMSOL has been performed to verify the results presented in Section III for both the airgap fluxes considered by the harmonic analysis and the slot leakage fluxes. It should be noted that the flux density levels in the stator and rotor cores and teeth are in the linear range (no saturation). When the 2-pole rotor winding is excited and the 6-pole rotor winding is open-circuit, the magnetic flux density and the induced voltage are shown in Fig. 5 and Fig. 6. The magnetic flux density and the magnetic vector potential distributions on the cross-sectional plane are shown in Fig. 5. The induced voltage generated by the 2-pole stator winding is shown in Fig. 6. The 6-pole stator winding has zero induced voltage.

Fig. 7 and Fig. 8 present the condition when only the 6-pole rotor winding is excited and the 2-pole rotor winding is open-circuit. Fig. 7 presents the 6-pole magnetic flux and magnetic vector potential distributions. It is clearly shown in Fig. 8 that 2-pole winding has no induced emf, while the 6-pole winding produces sinusoidal induced emf only when 6-pole rotor winding is excited.

Fig. 9 and Fig. 10 present the condition when both the 2-pole and 6-pole stator windings are excited. Fig. 10 presents the 2-pole and 6-pole stator induced voltages, and shows that the 2-pole and 6-pole voltages are independently generated without influence from the other rotor winding. It is to be concluded that the excitation of 6-pole rotor winding has a negligible impact on 2-pole stator winding, and vice versa.
B. Simulation Performance with Resistive Load

To investigate the performance under load and further demonstrate the fully decoupled winding properties, a simulation of the dual wound machine with resistive load condition has been studied. This simulation aims to verify that the 2-pole and 6-pole windings operate independently when both 2-pole and 6-pole rotor windings are energized. The power rating of the 2-pole generator is designed to be 560 W at 1500 rpm. The peak phase voltage and current are assumed to be 150 V and 2.5 A. The load resistance that connected for each phase of the 2-pole generator is therefore 60 Ω. For the 6-pole generator, the power rating is designed to be 220 W. The peak phase voltage and current are assumed to be 106 V and 1.4 A, so that the load resistance that connected for each phase of the 6-pole generator is 80 Ω. Fig. 11 presents the phase voltage and current for both windings when the 2-pole stator winding is supplying a 60 Ω resistive load and 6-pole stator winding is open circuit. It can be observed that the 2-pole winding operates at rated condition while 6-pole winding produces induced voltage but has no current. The voltage and current for the 2-pole stator winding in Fig. 11 do not exhibit ripples because the 2-pole generator is loaded and the winding is connected to the circuit, where the winding acts as a filter inductor. 

Fig. 12 shows the equivalent condition with the 2-pole winding in open circuit and the 6-pole winding with a resistive load of 80 Ω. Considering the results of Fig. 11 and Fig. 12 it is confirmed that the 2-pole and 6-pole windings can operate...
independently when either one is operating at its rated condition.

The case where both sets of windings are operating simultaneously at their respective rated loads is shown in Fig. 13. The stator voltages and currents with dual load are similar to the results with the single load conditions (Fig. 11, Fig. 12) which again shows that the 2-pole generator does not affect 6-pole generator and vice versa.

This section shows the simulation results when either and both windings are loaded at rated operation conditions, and confirms that they are fully decoupled due to both the airgap and slot leakage fields. The peak voltage of the 2-pole winding is 146 V and the peak current is 2.5 A, which means the power is 547.5 W at 1500 rpm. The peak voltage of the 6-pole winding is 105 V and the peak current is 1.4 A, which shows the power is 220.5 W.

V. EXPERIMENTAL TESTS

A. Test Platform

In order to further validate the concept, the proposed winding scheme is implemented and tested to confirm agreement between experimental results and simulation. The dual wound generator was rewound using the existing machine frame and the proposed winding design (Section II). The electric connection diagram of the dual wound generator is shown in Fig. 14. Fig. 15 shows a schematic of the experimental test platform, and Fig. 16 shows the experimental test platform at the University of Bath (U.K.), which is composed of the dual wound generator prototype, a DC motor, resistive loads, power sources and data acquisition equipment. The DC motor is used
as the prime mover, representing the prime mover in the electric ship application. The DC motor is rated at 5 kW and has a rated rotating speed of 3000 rpm. The DC motor has a rated field voltage of 200 V, with the field current of 1.1 A. The maximum armature current is 36.5 A. A LAB/SMS630 DC power supply is used to provide field current to the DC motor and a LAB/SMS5300 DC power supply to provide armature current. The torque of the DC motor can be controlled by changing the armature current, which is adjusted so as to achieve the target speed of up to 1500 rpm, monitored by a tachometer. On the generator side, the 2-pole and 6-pole rotor windings are supplied by EA-PS 8360-15 and LAB-SMP11200 DC power supplies to provide a one amp excitation current for the rotor windings. The two outputs of the dual wound generator are separately connected with their rated three-phase resistive loads. An oscilloscope is used to monitor and record the output voltage and current.

### B. Experimental Performance with Rotor Excitation under No-load Condition

In order to investigate whether one rotor winding would couple with the other stator winding the dual wound generator prototype is tested at no-load condition when only the 2-pole winding is excited, only the 6-pole winding is excited and when both rotor windings are excited.

Fig. 17 shows the stator terminal voltage with only the 6-pole rotor winding excited. The 6-pole stator winding generates a peak voltage of 132 V and the voltage of 2-pole stator winding is negligible.

Fig. 18 shows the stator terminal voltage with only the 6-pole rotor winding excited. The 6-pole stator winding generates a peak voltage of 132 V and the voltage of 2-pole stator winding is negligible.

When both 2-pole and 6-pole rotor windings are excited as shown in Fig. 19, the 2-pole winding has a peak induced voltage of 154 V and 6-pole winding has a peak voltage of 112 V. The voltage is slightly reduced compared with the results shown in Figs. 16 and 17 possibly due to saturation of the electrical steel. This no-load experiment also indicates that the three-phase outputs are perfectly balanced without the influence of the other winding.
C. Experimental Performance with Resistive Load

In order to confirm the performance of the system when either one or both windings are loaded, and whether each will affect the operation of the other, a resistive load of 60 Ω is used for 2-pole generator and a resistive load of 80 Ω for the 6-pole generator, as in the simulations. The three scenarios as in Section IV-B are tested: only the 2-pole generator loaded, only the 6-pole generator loaded and both 2-pole and 6-pole generators are loaded.

Fig. 20 and Fig. 21 show the condition when the 2-pole generator is connected to 60 Ω resistive load and the 6-pole stator winding is in open circuit. The 2-pole generator generates peak voltage of 144 V and peak current of 2.32 A, which is 501.1 W at 1500 rpm.

Fig. 22 and Fig. 23 present the generator voltage when the 2-pole generator is open circuit and the 6-pole generator is connected to 80 Ω resistive load. The 6-pole generator generates peak voltage of 106 V and peak current of 1.28 A, which is 203.5 W at 1500 rpm.

Fig. 24 and Fig. 25 show the results with the 2-pole generator connected to 60 Ω resistive load and the 6-pole generator connected to 80 Ω resistive load. The results show that the 2-pole and 6-pole generators can generate individual outputs with the resistive load without any influence from the other generator, demonstrating that they are electromagnetically decoupled.
The comparison between the simulation and experimental results are shown in Table VI for 2-pole stator voltage and Table VII for 6-pole stator voltage. The 2-pole and 6-pole simulation results match well with the experimental results. This again demonstrates that the 2-pole and 6-pole generator is substantially electromagnetically decoupled and therefore the change of load for one generator does not impact the operation of the other generator. The small changes can be due to end-winding coupling or due to the saturation effect.

**TABLE VI SUMMARY OF 2-POLE STATOR VOLTAGE UNDER DIFFERENT CONDITIONS**

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>Simulation (V)</th>
<th>Experimental (V)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-pole rotor winding excited</td>
<td>175</td>
<td>170</td>
<td>2.94%</td>
</tr>
<tr>
<td>Both rotor windings excited open circuit</td>
<td>150</td>
<td>154</td>
<td>2.59%</td>
</tr>
<tr>
<td>2-pole winding loaded 6-pole open-circuit</td>
<td>146</td>
<td>146</td>
<td>0.00%</td>
</tr>
<tr>
<td>6-pole winding loaded 2-pole open-circuit</td>
<td>147</td>
<td>148</td>
<td>0.67%</td>
</tr>
<tr>
<td>Both stator windings loaded</td>
<td>146</td>
<td>144</td>
<td>1.39%</td>
</tr>
</tbody>
</table>

**TABLE VII SUMMARY OF 6-POLE STATOR VOLTAGE UNDER DIFFERENT CONDITIONS**

<table>
<thead>
<tr>
<th>Operating condition</th>
<th>Simulation (V)</th>
<th>Experimental (V)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-pole rotor winding excited</td>
<td>125</td>
<td>132</td>
<td>-5.30%</td>
</tr>
<tr>
<td>Both rotor windings excited open circuit</td>
<td>107</td>
<td>112</td>
<td>-1.82%</td>
</tr>
<tr>
<td>2-pole winding loaded 6-pole open-circuit</td>
<td>106</td>
<td>108</td>
<td>1.89%</td>
</tr>
<tr>
<td>6-pole winding loaded 2-pole open-circuit</td>
<td>105</td>
<td>108</td>
<td>2.88%</td>
</tr>
<tr>
<td>Both stator windings loaded</td>
<td>105</td>
<td>106</td>
<td>2.86%</td>
</tr>
</tbody>
</table>

VI. SYSTEM ASPECTS AND DISCUSSION

There are several options for integrating the dual wound generator into an overall electric ship IFEP power system. The choices considered for this paper are as follows.

The system must supply high power to the propulsion and low power to the ships services, with a power ratio between 5 and 10 to 1. The total power required is of the order of tens of Mega Watts and in a warship application will need to be supplied by a gas turbine at a speed of the order of 3600 rpm. It will therefore be convenient to use the 2-pole output to supply the high-power propulsion at the usual frequency of 60 Hz. The supply for the ship services will then be at 180 Hz from the 6-pole winding.

However, the ship services supply will need to be either 60 Hz or any frequency if the supply is feeding power electronics conditioning equipment. The choice is then between converting the supply immediately at the generator output to 60 Hz via an electronic converter to give an AC supply or rectifying it to form a DC supply. The choice between AC and DC systems is application specific and is the subject of debate but it is believed that the DC system is a strong contender. However, in either case the current supplied by the generator output will be balanced.

The propulsion power will be conditioned by power electronic converters for control of the propulsion motors. The supply choice is to either rectify at the dual wound machine to form a DC supply or to supply the motor converters directly. In either case the current supplied by the generator will again be balanced. The test results in the paper are therefore all for balanced loads. However other conditions such as unbalanced loads will be considered in future work.

In this paper, the dual wound generator using wound-rotor is presented and experimentally verified. It is promising to extend the design methodology to a permeant magnet dual wound generator.

Outside of the proposed marine application the magnetically decoupled dual-wound generator has several potential applications, with the general case being any scenario where two independent power supplies are required, e.g. at different voltage levels. This scenario is especially widespread in the transport sector where an electric propulsion system requires high voltage power supply and auxiliary systems or ‘hotel loads’ require low voltage supply, typically 12 V, 24V or 48 V. In this case the dual wound generator could be especially relevant in the ‘series’ hybrid-electric powertrain architecture in which the transient vehicle power requirement is met by a small capacity high voltage battery pack, with the average power requirement being met by a high voltage generator powered by a prime mover (internal combustion engine or micro gas turbine) to maintain the charge of the battery pack. In this architecture the existing generator could have a secondary winding introduced to supply the low voltage systems, replacing the need for an alternator or DC-DC converter. The series hybrid-electric powertrain seems likely to fade in popularity as many governments introduce policy to pushing the passenger car sector towards full Battery Electric Vehicles (BEVs) and away from hybrid vehicles. However, the case for the haulage sector is less clear cut as the high energy requirements make BEVs less practical, and in this case the proposed system could be especially interesting as significant hotel loads often exist, for example for refrigeration.
For pure BEVs it should be noted that, since the two windings are completely decoupled, it is also possible to simultaneously operate them in different quadrants. This opens the possibility of dual wound traction motors in which the electric traction motor also contains a secondary winding which allows power take-off, replacing the alternator or DC-DC converter in the same manner described for the dual-wound generator.

VII. CONCLUSION

This paper presents a dual wound generator with 2-pole and 6-pole windings, which can generate two independent power supplies of different frequencies for an IFEP ship system. Previous studies on dual wound machines used same pole numbers for the two windings without the consideration of harmonic decoupling. The machine designed in this paper ensures that the two generators can operate independently. Both analytical calculations and 2D finite element COMSOL simulations validated by test results are applied to investigate the generator performance. The harmonic analysis and finite element modelling results show that the two outputs are fully electromagnetically decoupled as far as the airgap and slot leakage fields are concerned. A dual wound generator prototype is built and experimentally tested to validate the design and show that the end-winding leakage fields also do not couple. The dual wound generator prototype demonstrates that the 2-pole and 6-pole windings can generate individual power outputs without influence from the other winding. When the dual wound generator is integrated into an electric ship system, the power supply for the propulsion system can be independent from the power supply for the ship service system. Other potential applications, such as in electric cars, buses and trains are highlighted.

VIII. REFERENCES


IX. BIOGRAPHIES

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.

Dr Xiaoze Pei received the B.Eng. and M.Eng. degrees from Beijing Jiaotong University, Beijing, China in 2006 and 2008, respectively. She received the Ph.D. degree from the University of Manchester, Manchester, U.K. in 2012. She became a Research Associate at the University of Manchester. 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.
Prof Fred 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.

Han Wang received MSc at the University of Bath in the UK in 2019. He is currently under second year Ph.D. study in the University of Bath doing research on motor control and hybrid DC circuit breaker.

Chris Hodge MSc is the Chief Electrical Engineer at BMT Defence and Security. He is an Honorary Fellow of the IMarEST, a Fellow and former elected Trustee of the Royal Academy of Engineering and an Honorary Professor of Engineering at the University of Warwick. He served as the Chairman of the IMarEST Board of Trustees from 2009 to 2016 and has served as its President. He was made an Officer of the Order of the British Empire in Her Majesty the Queen’s Birthday Honours in 2015 for services to Royal Navy Engineering.

Oliver Simmonds MEng MSc is a Principal Engineer at BMT in Bath, UK. A Chartered Engineer, he has a background in both Mechanical and Electrical Engineering and has lead several major projects ranging from the delivery of a hybrid power and propulsion system for a Naval auxiliary vessel through to a wide range of technology studies and concept development work for future Power & Propulsion systems.

Dr Christopher Vagg received a MEng degree in mechanical engineering from the University of Bristol, UK, in 2009. He received the PhD degree from the University of Bath, UK, in 2014. From 2014 to 2019 he was head of Formula E electric powertrain with Renault Sport Racing (Paris, France). He is currently a Lecturer (Assistant Professor) in Advanced Automotive Propulsion Systems at the University of Bath, UK. His research activities include design of novel electric powertrains.

Dr Xianwu Zeng received his MSc and PhD at the University of Manchester between 2009 and 2014. He had a broad industry experience in power converter design. He was a lead power electronics engineer in GE grid solution before and was responsible to design valve unit for HVDC projects. He was also involved in several automotive projects including kW level DC-DC converter and inverter. In 2019, he joined the University of Bath as a Lecturer. His principle research interests include power electronics, motor drives, hybrid electric vehicles, and renewable energy interface systems.