Diode rectifier configurations with a multiphase synchronous generator

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Abstract
Direct current (DC) power networks are widely used in transport applications, often derived from a synchronous generator and diode rectifier. The use of more than three phases to reduce the DC voltage ripple eliminates the DC filter capacitance and incorporating multiple phases into the generator avoids the need for bulky phase-shifting transformers. Recent trends have moved away from high phase-number machines to multiple winding sets, in order to enhance fault tolerance. This study shows how the number and arrangement of these phase sets and rectifier circuits should be selected to improve steady-state performance, by suppressing unwanted harmonics. Complex harmonic analysis expressions are developed for the wound field, salient, synchronous generator incorporating both saliency and saturation, allowing general design principles for avoiding circulating harmonic currents and high peak diode currents to be identified. The model is validated on a 15-phase, 19kVA laboratory machine, reconfigurable as five 3-phase sets and three 5-phase sets. The results show that for this example, multiple 3-phase, winding sets can give better performance than the high phase-number system, with lower stator copper loss and higher power factor.

1 | INTRODUCTION

Multiphase synchronous generators with diode rectifiers can provide power for direct current (DC) networks and have been evaluated in applications including aircraft [1,2], ships [3–6], and wind turbines [7]; DC power is already the norm for road vehicles [8]. In a conventional fixed-frequency alternating current (AC) grid, the synchronous generator speed is tied to the grid frequency. But if the prime mover speed varies, for example due to flight requirements in an aircraft, the generator needs either a fully rated AC/AC converter or a continuously variable transmission to maintain a fixed frequency output. By rectifying to DC, the speed constraint is removed, so multiple generators can operate at different speeds on the same DC network, enabling the efficiency of the prime movers to be optimised [9]. In [10–12], weight and volume savings have been identified for marine and aircraft over equivalent AC networks and integration of energy storage is easier [13].

The advantages of using a multiphase machine to supply a bridge rectifier have been stated as reducing the DC voltage ripple and torque ripple [9,14], which can eliminate the DC filter capacitor, compared with a three-phase, six-pulse system [14], thus reducing the DC fault current. Compared with a multi-pulse rectifier [15], external phase-shifting transformers are not required. Multiphase windings provide additional degrees of freedom for the stator current, improving fault tolerance [16–18], which is particularly important for aircraft applications [11].

In an active rectifier, the control forces the currents to be close to sinusoidal, adjusting the magnitude and phase to compensate for open-circuit faults and suppress harmonics. However, the boost action of the active rectifier requires dc-link capacitance, so DC short-circuit faults are more severe than in the uncontrolled rectifier [19]. In a diode rectifier, currents can be highly distorted [14], and the harmonic content is controlled by the design and connection of the windings and rectifiers. Split-phase systems (multiple sets of three-phase windings and rectifiers) have been cited in [3,6,9,20–22] as improving fault tolerance, but to date, no comparison of their steady-state performance has been identified in the literature.

Multiphase applications [16–18] focus on induction and permanent magnet (PM) machines, rather than the wound field...
synchronous machine (WFSM). Three-phase WFSM generator-rectifier systems (GRS) are widely used in vehicle alternators, because the field can be used to regulate the voltage or deactivate it during a fault. Modelling of their fundamental behaviour has been addressed extensively, for example by Sudhoff [23] and can correctly predict operating point and stability [24] but is not suitable for determining losses or voltage ripple. Dynamic d-q modelling of the multiphase WFSM [25] generally assumes sinusoidal windings; extended d-q models [2] still neglect stator harmonics that are due to interaction of stator magnetomotive force and rotor saliency [26,27]. Recent work [20,22,26,28] advocates the use of harmonic winding-function (WF) expressions to calculate coupling inductances for multiphase WFSMs. Harmonic analysis is also used in multiphase induction machines [29] and three-phase WFSM damper design [28]. As Abdel-Khalik’s [30] study shows, the WF can also be equivalently expressed in a Complex Harmonic Analysis (CHA) form. The alternative is to use finite element analysis (FEA) to model the spatial variations in the magnetic circuit, but this can be time-consuming [26], since damper currents are asynchronous [27]. Moreover, the FEA results do not explicitly link problematic harmonics to machine design parameters.

The aim of this study is to evaluate the steady-state performance of split-phase systems compared with a single, multiphase GRS, in order to select an appropriate winding design and circuit topology. Section 2 summarises the GRS analysis, which is validated in Section 3 against experimental results, using a reconfigurable 15-phase Cummins BCI162 G generator. In Section 4, the model is used to evaluate GRS topologies, comparing a single 15-phase GRS with two split-phase combinations: five sets of 3-phase and three sets of 5-phase diode bridges, respectively. The results show that the choice of connection topology significantly influences GRS steady-state performance, in terms of metrics such as stator copper losses, DC voltage ripple, and overload capability.

2 | ANALYSIS AND MODELLING

An overview of the GRS system simulation is shown in Figure 1. The generator is modelled using harmonic mutual winding inductance calculations, as developed in the appendix. Significant harmonics can be identified individually at this stage, for design refinement and to ensure appropriate angular resolution for the inductance matrix. The inductance look-up table had a resolution of 0.7°, with linear interpolation between points. Details of damper circuit modelling, saturation factor and leakage calculations are also given in the appendix.

The value of the CHA modelling is illustrated in Figure 2, which shows the magnitude of back electromotive force (EMF) per amp of field current (unsaturated) for a 15-phase machine, for a single fully pitched (FP) stator phase winding (a), compared with that for a winding short-pitched (SP) to 80% (b), for combinations of rotor harmonic $\nu$ and airgap harmonic $l$. The rotor winding is designed to cancel fifth harmonic, since there are no terms for $\nu = 5$, but rotor fundamental combines with airgap sixth harmonic to induce 70% of total stator fifth

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**Figure 1** Simulation system diagram

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**Figure 2** Comparison of back electromotive force harmonics in a single stator sub-phase for (a) fully pitched (FP) and (b) short-pitched (SP) to 80% for 1A field current at 1000 rpm
harmonic in the FP case (a), as predicted by Equation (A10). Short pitching the stator to 80% sets the fifth harmonic stator winding coefficient to zero in (b), eliminating fifth harmonic but reducing the fundamental to 95.1% of the FP value.

Cancellation of zero-sequence EMF-induced currents (multiples of $m^{th}$ harmonic in an $m$-phase winding set) can also be achieved by eliminating circulating current paths, for example using a star-connected winding with an isolated neutral point, with no reduction in fundamental. Figure 2 also illustrates that rotor third harmonic combined with airgap second harmonic ($\nu = 3, l = -2$) significantly affects fundamental stator voltages in both the SP and FP cases.

SP to 66.7% would eliminate third harmonic but reduces the fundamental to 86.6% of FP.

The generator is modelled in state-space form. For the machine in Figure 1, state variables comprised 15 stator, 1 rotor and 8 damper currents $\bar{I}$, with input voltage vector $\bar{V}$.

$$\bar{I} = [L]^{-1} \int (-\bar{V} - [R]\bar{I})dt$$  \hspace{1cm}(1)

In non-salient multiphase machines, the extended Clarke's transform is used to map to a fundamental $(\alpha\beta)$ plane and a set of decoupled higher order $(xy)$ planes which link to specific combinations of time and space harmonics [30,31]. However, as Figure 2 and Equation (A10) show, saliency (and cross-saturation, [31]) leads to coupling between $\alpha\beta$ and $xy$ planes, removing any computational advantages. The GRS has significant space and time harmonics, so for modelling accuracy, phase currents were retained as state variables, and the Clarke's transformation was not used.

As Figure 1 shows, the diode rectifier is modelled in the PLECS® circuit solver, as a built-in package in Simulink®. Unlike the connection matrix approach used by Huang et al. [20], PLECS allows easy reconnection of components to represent the different circuit topologies, incorporates good state event detection, and has no hidden snubbers [32]. Diode parameters were set to match the experimental system (VS-60MT120KPbF), with 1 V forward conduction voltage and 1.07 V turn-on voltage threshold. This is suitable for marine applications, but devices would differ in a 400 Hz aircraft application. Simulink® is used to solve the generator circuit equation in integral form, with an ode23 t solver and an error tolerance of $10^{-4}$. The rotor field excitation voltage was constant and for the short-circuited damper circuits, loop voltages were set to zero. Stator input voltages for the machine model are measured from the PLECS® circuit model of the diode rectifier. Output phase currents from the generator model are represented as current sources in the rectifier circuit.

3 | MODEL VALIDATION AGAINST EXPERIMENTAL RESULTS

The experimental work uses a reconfigurable 15-phase Cummins BCI162 G generator (rated at 19 kVA, 332 V, 50 Hz and 3000 rpm, but limited to 1800 rpm for safety reasons, with 5 A no-load and 20 A full-load field current) [33]. The test rig is shown in Figure 3 and loading conditions are summarised in Table 1. The 2 V DC load was the lowest available, so tests E and F were at reduced power. Voltage and current were measured with a differential voltage probe (TA041) and current transducer (LA55-P) connected to a Tektronix TDS2024 D oscilloscope. Angular position was measured with an incremental encoder, using an index pulse for absolute position.

Figure 4 compares results between simulation and experiment for the 15-phase connection, in star and polygon connection, with both SP and FP windings (a-d), and for split-phase connection arrangements of five-phase (e) and three-phase sets with SP windings with parallel-stacked diode rectifiers (f), as listed in Table 1. Figures 4a and d show that the CHA model matches within 5% on generator and DC output voltages, respectively. Figures 4b and c show a match within 10% on currents, with (b) showing generator phase current, and (c) rectifier current for the generator A phase in star, and AB connection in delta. Differences between fundamental and overall rms currents, most obvious in tests B–E, indicate a high degree of harmonic distortion in both the simulated and experimental results. These results validate the simulation for comparison of generator connection topologies and show the importance of full harmonic modelling.

Figures 5 and 6 compare experimental (left) and simulated (right) waveforms, with a good match on overall shape. Waveforms have been selected that represent the range of accuracy of fit, with further results available in [33]. Diode currents are the most distorted waveforms, so the least easy to predict accurately, although Figure 4 shows that rms values are correct. The simulated diode current in the FP polygon case in Figure 5a and SP polygon case in Figure 6b do not predict the dip seen in the experiment, although it is correctly predicted for higher field excitation [33]. The FP star-connection, in Figure 5c, shows some phase lag between generator voltage and diode current. In the simulation, 0.1 Ω resistors (5% of DC load) were included in both positive and negative terminals of diode rectifiers for the parallel-stacked topologies.
TABLE 1  Experiment loading conditions

| Test | Phases | Connection | Field current a | DC load Ω | Power DC kW |
|------|--------|------------|-----------------|-----------|-------------|
| A    | 15     | Poly FP   | 12              | 3.3       | 8           |
| B    | 15     | Poly SP   | 12              | 3.3       | 8           |
| C    | 15     | Star FP   | 16              | 2         | 6           |
| D    | 15     | Star SP   | 16              | 2         | 6           |
| E    | 3 sets of 5ph | Poly SP | 16 | 2 | 4 |
| F    | 5 sets of 3ph | Poly SP | 16 | 2 | 1.5 |

Abbreviations: DC, direct current; FP, fully pitched; SP, short-pitched.

TABLE 1

(a) Sim Fund  Exp Fund  Sim All  Exp All

(b)

(c)

(d)

FIGURE 4  Comparison of simulation and experiment for
(a) generator voltage, (b) generator current, (c) diode current and (d) direct
current voltage; ‘Fund’ = fundamental, ‘All’ = overall rms

(Tests E and F), representing contact resistances in the test rig.
Contact resistances, field current and saturation were found to
have the largest effect on model fit. In contrast, diode reverse
recovery characteristics were found to be insignificant so were
omitted.

4  EVALUATION OF CONNECTION TOPOLOGIES

The aim of this section is to simulate and evaluate the steady-
state performance of split-phase systems compared with a
**TABLE 2**  GRS Connection options

|                              | 3-phase sets | 5-phase sets | 15-phase  |
|------------------------------|--------------|--------------|-----------|
| Phase sets                   |              |              |           |
| Connection within set.star/polygon |              |              |           |
| FP factor                    | 100%         | 100%         | 100%      |
| SP factor                    | 86.7%        | 95.1%        | 95.1%     |
| Rectifier inter-connection    |              |              |           |
| series/parallel               |              |              |           |

**FIGURE 6**  Comparison between experiment (left) and simulation (right) for (a) three 5-phase sets of polygon short-pitched (SP) and (b) five 3-phase sets with delta SP, both parallel-stacked.

**FIGURE 7**  Direct current power versus load resistance for (a) 15-phase, (b) series stacked and (c) parallel-stacked diode rectifiers. FP, fully pitched; SP, short-pitched.

x-axis, Resistance Ω; y-axis, Power kW.
single, multiphase GRS, and identify principles for selecting the connection topology. The example compares a 15-phase winding with two split phase configurations: three 5-phase sets and five 3-phase sets. As summarised in Table 2, coils can be SP for harmonic elimination and connected in star or polygon. In [20], split-phase rectifier outputs are connected in parallel to allow a faulty rectifier to be disconnected, but [6,7] propose a series connection with a fault bypass switch, so both options are considered.

For a fair comparison, the rotor and stator geometry were kept constant, fixing the rotor and airgap spatial harmonics. The rotor field was set to its full-load value of 20 A and the speed to 3000 rpm. The DC output voltage differs with topology, so the load resistance was adjusted to deliver 15 kW power to the DC load in all cases. The power versus load resistance curve, Figure 7, was found by simulation. Figure 7 shows two resistance values corresponding to 15 kW; the higher value was used, giving the stable operating point. The figure also shows peak power capability. In a practical GRS design, the number of turns could be changed to set the voltage.

Figure 8 compares generator phase voltage for (a) fundamental and (c) total harmonic distortion (THDv) and DC output (b) voltage and (d) ripple for different connection topologies. Figure 9 shows corresponding (a) generator phase current, (b) rectifier input current, as well as (c) generator apparent power and (d) stator copper losses. Iron losses have been omitted, due to lack of electrical steel data. In the star connection case, rectifier and generator currents should be identical; differences of less than 1% are due to the use of burden resistors in the simulation. These are backed up by selected waveforms for a 15-phase rectifier in Figure 10, and for the split phase rectifier systems in Figure 11. For ease of comparison, voltage axes show 150 V per division throughout and current axes are 20 A per division for the series-stacked and 15-phase systems and 30A per division for parallel-

**FIGURE 8** (a) Generator fundamental phase voltage, (b) rectified DC voltage, (c) generator total harmonic distortion and (d) DC voltage ripple for the different connection topologies. FP, fully pitched; SP, short-pitched. 
Abbreviation: DC, direct current.

**FIGURE 9** (a) Generator rms phase current, (b) rectifier rms current, (c) generator apparent power and, and (d) copper loss for the different connection topologies. FP, fully pitched; SP, short-pitched.
stacked. Trends can be identified, and the models allow their significance to be quantified for this example, with items listed in order of significance.

4.1 | Effect of circulating currents

Section 2 identified the presence of zero-sequence harmonics in the FP winding. Figure 9 shows that the split-phase FP polygon results have high generator rms currents, resulting in high stator copper losses and apparent power. Figure 8 shows high THDv, and Figure 7 shows low peak power capability. For the three 5-phase sets, fifth harmonic current can be seen in the simulated waveforms in Figure 11a and c and experimental results, Figure 6a. Similarly, circulating third harmonic currents were seen in the five 3-phase sets. Hence elimination of zero-sequence currents in the split-phase designs, either through short-pitching or a star connection should be a priority. In the 15-phase machine, 15th harmonic current is attenuated, due to both a lower harmonic voltage magnitude and higher impedance.

4.2 | Effect of high phase number

In the diode rectifier, the whole load current usually flows just in two diodes (the ones with the highest voltage difference between them). Figure 10 shows that in the 15-phase machine, the rectifier current has a poor form factor, with a high peak value and short duration, giving a high rms diode current, and high current stress on the devices. The theoretical conduction period, neglecting commutation, varies as $1/m^{th}$ cycle [14], although in practice, extended conduction at low current is seen as extra blips in Figure 10b. Figure 9 confirms high rectifier and generator currents in the star connection, which cause high copper losses and low peak power. The generator performance is better in the 15-phase polygon case, both because the DC voltage is higher, so the current is lower, and because it is shared between two parallel paths in the generator [14]. In the split-phase cases, parallel stacking allows current sharing between phase sets, and series stacking increases the DC voltage, reducing the current per phase set. The conduction time is longer because there are fewer phases within each set. Both these features improve current form factor, making a split-phase topology attractive.

4.3 | Comparison of FP and SP

FP windings have a higher fundamental pitch factor than the SP windings, as given in Table 2, so the fundamental generator voltage and DC link voltage are higher with FP than with SP for all results in Figure 8. However, the FP windings show a higher THDv than SP, since the SP factor is selected to cancel a significant harmonic. For the same load power, a higher voltage gives a lower current, so generator phase currents are lower with FP than SP in Figure 9a (except in the FP polygon connection, which has already been discussed in Section 4.1). Lower current results in lower apparent power Figure 9c and reduced copper losses Figure 9d. The difference is less apparent for the 15-phase connection, where the reduction in winding factor is smaller.
4.4 | Series or parallel stacking

The DC voltage magnitude depends on the connection arrangement. The use of split-phase systems in series increases the total DC voltage and reduces the current, with the lowest DC current for the stack of five 3-phase rectifiers and highest for the single 15-phase case. Split phase systems in parallel increase the total DC current and show slightly more current per diode rectifier due to circulating harmonics, which gives generally lower power factor and higher stator copper loss than the corresponding series-stacked system, shown in Figures 8 and 9. The experimental work showed it was also more difficult to manage current sharing between rectifiers, which was sensitive to connection resistance.

4.5 | Summary

From Figures 7–11, five series-stacked 3-phase sub-machines, connected as FP and star, give the lowest stator loss,
lowest apparent power, so highest power factor, highest DC link voltage and high maximum power capability. DC voltage ripple is acceptable, but if this is a priority, then Figures 7–9 show that the polygon connection of three sets of 5-phase, SP, with series or parallel stacking, and the 15-phase SP polygon connection all give lower voltage ripple, with acceptable generator performance. For aircraft, MIL-STD-704F [34] allows 4.4% variation at 270 VDC. The simulation methodology allows such trade-offs to be evaluated.

5 | CONCLUSIONS

This study investigates the benefits of a GRS with multiple split phase windings and rectifiers for a DC power source. It presents a computationally efficient model for the GRS, combining a CHA model of the generator with a PLECS circuit model of the rectifier, which includes new expressions for space and time harmonics. The model is validated against experimental results with acceptable accuracy for comparison of connection methods.

The analysis shows that airgap saliency introduces harmonic frequencies that would not be present in a non-salient machine; this conclusion would also be valid for interior permanent magnet machines. Conduction paths that do not link the load, through parallel-connected rectifiers and polygon-connected windings, lead to high circulating harmonic currents, which result in a lower power factor and increased copper losses. Zero-sequence harmonics can be predicted with CHA and eliminated by SP, at the cost of a reduced winding factor and hence lower peak power capability. Isolated star connections also eliminate zero sequence components, but the simulation shows that for the star connection, increasing the phase number increases current distortion, giving a lower power factor, higher copper losses in the generator and higher current stress on the diodes. Split-phase sets are shown to reduce the diode stress and generator loss. These are general trends, independent of geometry or phase number, which have not previously been considered in multiphase machines.

The model is used to compare multiple split-phase submachine/rectifier systems with a single, 15-phase system. Five sets of three-phase, star, FP, series-stacked rectifiers are shown to provide the best option in terms of generator copper losses, peak power capability and power factor, although other options provide lower DC voltage ripple. This study has specifically addressed healthy performance, supplementing [20,22] on fault tolerance, giving new insight that the use of split-phase GRS to improve fault tolerance can also give steady-state performance benefits.

The proposed models are valuable for initial system sizing studies for marine and aircraft DC power sources. The model validation identifies the significance of saturation at high field excitation. At the detailed design stage, the simulation remains valuable for dynamic studies, where FEA-generated inductances [26] could replace the initial CHA values.

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APPENDIX A—GENERATOR DATA

| Table A1 | Generator data |
|----------|----------------|
| Symbol   | Quantity       | Value               |
| μ₀       | Permeability of vacuum | 4π×10⁻⁷ Hm⁻¹ |
| W        | Machine axial length | 0.1372 m            |
| R        | Stator inner radius | 0.0875 m            |
| Nₛ       | Number of stator slots | 30                 |
| Nₑ       | Conductors per stator slot | 7            |
| wₛ       | Stator slot opening | 0.0038 m            |
| P        | Rotor pole pairs | 1                   |
| Dₑ       | Rotor outer diameter | 0.1726 m            |
| Dₛₑ      | Damper outer diameter | 0.165 m            |
| Dₛₒd    | Min. Rotor coil OD | 0.108 m             |
| wₛₒd    | Damper slot opening | 0.00292 m          |
| dᵣ       | Angle between rotor coils | 12.66° |
| wᵣ       | Single rotor coil width | 23.34 mm         |
| Nᵣ       | Turns per rotor coil | 195                 |
| M        | Number of phases | 15                  |
| Rₛ       | Stator per phase resistance | 139 mΩ |
| Rᵣ       | Rotor resistance | 1.728 Ω             |
| Rₛₑ      | Damper bar resistance | 120 μΩ            |
| Rₛₒ      | Damper end resistance (1,3,5,7) | 96.6 μΩ   |
| Rₛₒd    | Damper end resistance (2,6) | 177 μΩ           |
| Rₛₒd     | Damper end resistance (4,8) | 665 μΩ           |

APPENDIX B—CHA GENERATOR MODEL

In CHA, the spatial winding distribution cₜ for winding t, is defined in terms of local angle θ (θₛ or θᵣ for the stator or rotor respectively).

\[ cₜ(θ) = \sum_{\nu=-\infty}^{\infty} Cₜ ν e^{jνθ} \]  \hspace{1cm} (A1)

In the complex Fourier notation, the νᵗʰ winding coefficient Cₜ is given by Williamson, & Smith [35]:

\[ Cₜ = \frac{1}{2\pi} \int_{0}^{2\pi} cₜ(θ) e^{jνθ} dθ = \frac{jNₚb}{\pi P} K_p(ν) K_s(ν) K_d(ν) K_e(ν) e^{jνθ} \]  \hspace{1cm} (A2)

where \( K_p(ν) \) is the pitch factor, \( K_s(ν) \) is the stator slot opening factor, \( K_d(ν) \) is the distribution factor, \( K_e(ν) \) is a factor relating to the double-layer winding layout, and \( Nₚb \) is the number of turns per phase group, computed from the geometric parameters in Table A1, following [35,36].

Rotor angle is related to the physical rotor angle \( θ_m \) and pole pairs, \( P \). Rotor field and damper windings can be written in terms of stator angle, using a change of variables

\[ θ_r = θ_s = \rho θ_m \]  \hspace{1cm} (A3)

The inverse airgap variation, \( g^{-1} \), can also be represented as a harmonic series [36]. Due to rotor saliency, it depends on the rotor angle and by symmetry, only even harmonics are non-zero. The inverse airgap distribution, \( G \) has \( l \) harmonic components.

\[ \frac{1}{g(θ)} = \sum_{l=-\infty}^{\infty} G e^{-jlθ} = \sum_{l=-\infty}^{\infty} G e^{-jl(θ−ρθ_m)} \]  \hspace{1cm} (A4)

For the geometry and notation given in Table A1, the inverse airgap coefficient is given by

\[ G = \frac{2}{πl} \left[ \left( \frac{1}{(r-Dₑ/2)} - \frac{1}{(r-Dₒd/2)} \right) \sin \left( \frac{π}{2} - \frac{d_r}{2} - w_r \right) \right] \]  \hspace{1cm} (A5)

The magnetic flux density due to winding \( w₁ \), with current \( i_{w₁}(t) \) can be found by integration [36], as per Equation (A6), where ζ = \( l \) for a stator winding and \( ζ = l + ν \) for a rotor winding. Saturation factor \( k \) will be discussed later.

\[ B(θₚ, θ) = kμ₀g(θ) \int_{t=0}^{2π} c_{w₁}(θₚ) i_{w₁}(t) dθ \]  \hspace{1cm} (A6)

The coupled flux from winding \( w₁ \) into an arbitrary second winding \( w₂ \) can be found by integration of the flux density linking this second winding, with harmonics denoted by \( μ \).

\[ \psi_{w₂w₁} = \frac{2π}{0} \int c_{w₂}(θₚ') \int B_{w₂}(θₚ, θ) dθᵣ \]  \hspace{1cm} (A7)

Since the skew means the flux linkage depends on the axial position of the generator, the total linked flux \( \psi_{w₂w₁} \) is found by integration along the generator axial length for the flux linkage at arbitrary axial position \( w' \) of the generator.
The general form of the mutual coupling inductance is given in Equation (A9).

\[
L_{w_2w_1} = kL_0 \sum_{l=-\infty}^{\infty} \sum_{\mu=-\infty}^{\infty} \sum_{\nu=-\infty}^{\infty} \frac{-\nu - \mu}{\nu(l + \nu)} C_{w_1} C_{w_2} G_{1} \bar{K}_{sk} e^{j\rho \theta_{m}} \tag{A9}
\]

Coefficient \( \gamma \) is a linear combination of harmonic indices \( \mu \), \( \nu \) and \( K_{sk} \) is the stator harmonic skew factor [37], as shown in Table A2. For non-zero flux linkage, Equation (A10) must be satisfied, and by symmetry, \( l \) must even, and \( \mu \) and \( \nu \) must be odd multiples of pole pairs.

\[
\nu + \mu + l = 0 \tag{A10}
\]

The back EMF of a single-phase stator winding, due to field current \( \dot{i}_r(t) \) can be expressed as Equation (A11).

\[
E_s = kL_0 \rho_0 m \dot{i}_r \sum_{l=-\infty}^{\infty} \sum_{\mu=-\infty}^{\infty} \sum_{\nu=-\infty}^{\infty} \frac{-\nu - \mu}{\nu(l + \nu)} C_{\nu} C_{\mu} G_{1} \bar{K}_{sk} e^{j\rho \theta_{m}} \tag{A11}
\]

Field excitation in a WFSM can vary considerably, so saturation is included using coefficient \( \hat{k} \). This can be characterised using fundamental back EMF from experimental open-circuit measurements or static FEA, as a function of field current [24,38,39], as shown in Figure A1. The look-up-table for factor \( \hat{k} \) is referenced using total magnetising current, \( I_f \), as the phasor sum of the field current, \( \dot{I}_f \), and rotor-referred stator \( d \) and \( q \) axis currents \( \dot{I}_{sd} \) and \( \dot{I}_{sq} \), which is appropriate for main flux saturation [38,39].

\[
I_f = |\dot{I}_r + \dot{I}_{sd} + j \dot{I}_{sq}| \tag{A12}
\]

The damper circuit is analysed by solving for the circulating currents in each short-circuited damper bar loop [28,40,41], together with the damper bar and end resistances. Equation (A9) only gives mutual inductances, so slot leakage inductances were found by using 2D FEA and stator end winding leakage inductances were measured using an LCR metre (Agilent 4284A), with the rotor removed. Rotor leakage inductance was being neglected as the rotor side is operating at DC. Unlike a three-phase GRS, where the sub-transient time constant of the generator depends on the damper leakage inductance, in a multiphase machine, damper leakage has been shown to have minimal effect on commutation [21]. Hence damper leakage inductances are only important for numerical stability and have been taken as a nominal 10% of the mutual values.