

Article

Vibration Assessment Due to Stator and Rotor Interturn Faults in a Doubly Fed Induction Generator for Wind Turbine Application

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Abstract

All rotating electrical machines are susceptible to vibrations arising from electromagnetic (EM) forces, electrical faults, mechanical defects, imbalance, and structural resonance. In Doubly Fed Induction Generators (DFIGs), such electromechanical vibrations are especially important because they can degrade reliability, increase noise, and lead to severe damage if resonance-prone operating conditions are not identified in time. Although fault diagnosis in DFIGs has been widely investigated using current, voltage, and flux signatures, comparatively fewer studies have examined fault-specific vibration behaviour under stator and rotor interturn faults (ITTFs), particularly through a coupled EM structural framework. In addition, prior vibration-based studies have not examined the influence of end winding ITTFs, its location, severity, and modal interaction investigating resonance risk. This paper considers vibration characteristics of a variable-speed 2.8 MW DFIG used in a grid-connected Type-3 wind turbine unit (WTU) at no-load operating condition. The DFIG is modelled in ANSYS Academic Research v 2022 R2 Maxwell for EM behaviour assessment for ITTFs in both stator and rotor windings along with modal analysis (MA) in ANSYS Workbench to examine the undamped stator and rotor modes over a range of frequencies. This coupled approach enables identification of vibration signatures associated with different ITTF types. The results show the magnetic flux density near faulty end-winding region increases with fault severity and ranges from 4.19 T to 4.39 T in proximity to faulty windings. A dominant modal frequency band of 60–65 Hz is identified, where stator and rotor modes coincide, creating probable resonance conditions. A severe vibration response is observed for single-phase stator ITTF, showing an amplitude of 2116 mm/s at 480 Hz for a larger number of shorted turns, indicating that asymmetric faults can produce stronger EM excitation than multi-phase faults. The main contribution of this paper is demonstration of a fault-specific, MA and vibration-based Condition monitoring system (CMS) implementation workflow for a DFIG. Unlike prior vibration-based studies that primarily focus on general machine vibration, mechanical faults, bearings, etc., this paper links stator and rotor ITTF induced EM excitation to modal characteristics, resonance behaviour, and measurable vibration signatures, establishing vibration analysis (VA) as a practical complementary technique for CMS of ITTFs in DFIGs.

Keywords: condition monitoring system (CMS); Doubly Fed Induction Generator (DFIG); interturn fault (ITTF); modal analysis (MA); modal frequency (MF); vibration analysis (VA)



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1. Introduction

Doubly Fed Induction Generators (DFIGs) are widely used in wind turbine systems globally, making them crucial electric machines to study and understand. DFIGs used in Wind turbine units (WTUs) are studied in this paper, which are capable of operating in both standalone and grid-connected modes. High-power-rating converters are used for the grid-connected mode of WTUs. A typical rotor-side converter (RSC), grid-side converter (GSC) and 2.8 MW DFIG [1] based WTU are shown in Figure 1. The stator of the DFIG is directly connected to the grid, whereas the rotor is connected to a back-to-back RSC and GSC via slip rings. Conventionally, GSC act as a current source with a high parallel impedance and maintains a constant DC link voltage. The synchronous speed of the DFIG is defined as $n_s = 120 * f / p$, and if the rotor speed is n_r , the slip is defined as $s = (n_s - n_r) / n_s$ where f is the nominal frequency and p is the number of poles of the DFIG. Therefore, a DFIG operates at synchronous speed if $s = 0$, subsynchronous speed if $s > 0$, and super-synchronous speed if $s < 0$. Depending on the DFIG rotor speed, the back-to-back RSC and GSC convert AC to DC to AC, as shown in Figure 1. When $n_s > n_r$, the GSC converts the grid AC voltage to DC, which is converted back to AC by the RSC absorbing active power from the grid. However, at high wind speeds, when $n_s < n_r$, DFIG delivers active power to the grid [2]. DFIGs are vulnerable to vibrations that can be caused by high wind speeds, varying excitation, load, electromagnetic (EM) forces, electromechanical faults, mechanical imbalances, or structural resonances [3]. Faults on WTU's generator are difficult to detect until the last moment, which usually affects the machine itself and nearby or subsequently the entire grid network by cascading events. It is even more common for small and weak grid networks with small Short-circuit ratios (SCRs), such as remote and island grids in Australia, the UK, Norway, Spain, Chile, and China [4].

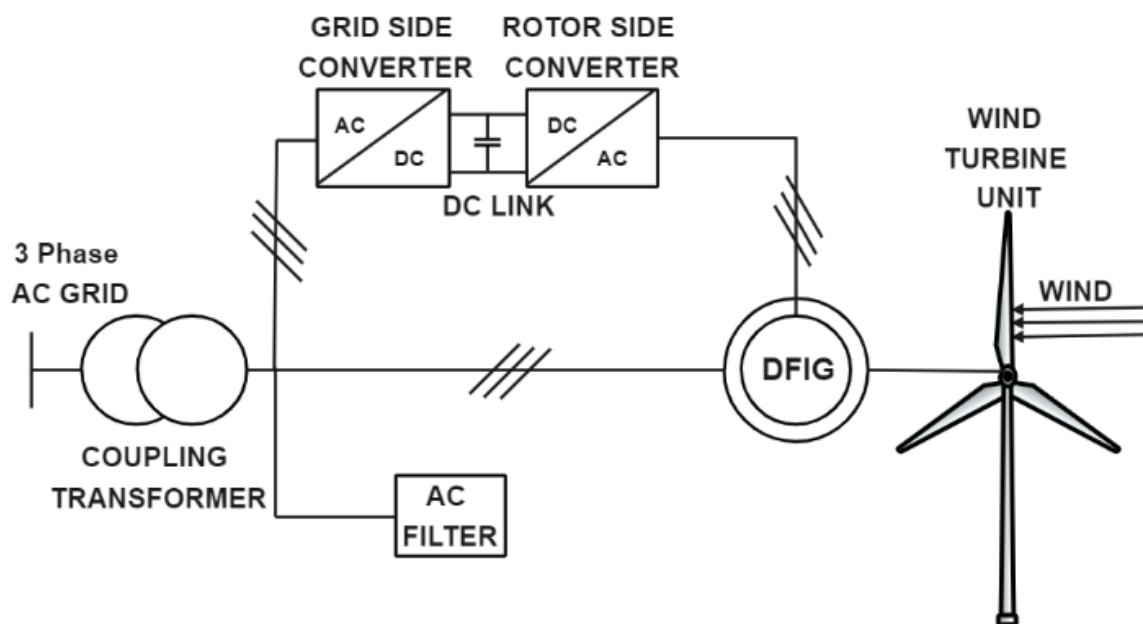


Figure 1. Single DFIG wind turbine unit system.

DFIGs could at times be unreachable to repair because of the location of WTUs, which could only get worse if they are offshore as well. It is not only difficult for service engineers but also adds to the costs of power supply downtime, utility, and machine manufacturing companies. Therefore, it is imperative to develop robust machine design.

There have been numerous examples of wind farm failures due to several reasons worldwide, leading to blackouts for hours. For example, nine wind farms triggered protective shutdowns instead of riding through the faults in South Australia in 2016 [5],

Hornsea wind farm tripping in the UK in 2019 [6], and recently in Spain and Portugal in April 2025 [7], forcing power plants to blackstart. There is no direct evidence of interturn faults (ITTFs) causing grid blackouts, but SC contribution from DFIGs and eventually Point of Connection (POC) of Wind Power Plant (WPP) can cause a voltage dip at the POC leading to grid instability [8,9].

Stator and rotor ITTFs can occur for a number of reasons, such as thermal aging of the machine due to continuous operation at high temperature, and overloading causing high current in the windings. This can cause hot spots and accelerate winding damage due to transient events such as lightning, voltage surges, grid faults, harmonics [10] and unbalanced loads. ITTFs could also occur due to loose laminations causing abrasion of insulation between turns, and contamination due to environmental reasons such as moisture, salt, pressure, winds, etc., in the case of offshore turbines [11–13]. Because of rotor ITTFs, the stator can also be at risk and vice versa.

1.1. Literature Review

SC faults form 21% of the faults occurring in electrical machines and it is reported that most SC faults begin as ITTFs [14,15]. It is understood that several phase-to-ground or phase-to-phase faults started as undetected ITTFs, which eventually grew and proliferated until catastrophe. Approximately 80% of stator winding (SW) electrical failures are linked to depreciated turn-to-turn insulation, often resulting from electrical stresses, such as transient voltage surges experienced by the generator. Accordingly, the implementation of a real-time detection technique for ITTFs is essential [16]. Another common reason is defective slip brush contact and carbon dust due to slip-ring wear and tear. This is a practical problem faced by manufacturers for all types of rotating machines with slip rings. Early detection of slip-ring unit defects, for example, ref. [17], can avert expensive repairs. Thus, the total loss of the generator unit, which often leads to substantial costs and time, can be avoided. As the rotor is energized by slip rings and carbon brushed on one end and RSC on the other, slip-ring malfunction can be a crucial cause of rotor ITTFs, thermal hotspots, and SCs [18].

Table 1 compiles a comparison of existing ITTF identification techniques, their advantages and limitations. An analytical model for power hardware-in-loop emulation of induction machine stator ITTFs studied in [19] presents fault emulation by using voltage behind reactance and considers nonlinearity of the leakage inductance. Stator ITTFs diagnostics of an induction motor (IM) are understood in [20] by utilizing Clarke Vector Hodograph shape which offers a significant advantage over traditional methods such as Fourier transform, short-time Fourier transform, and Hilbert Huang transform. Negative sequence current and current harmonics of IM stator current are used to generate a fault index to detect ITTF in [21]. The fault index increases with the increase in ITTFs in the machine which gives a prior awareness of ITTF level. In the study [22], the authors used negative sequence voltage components for detection of stator ITTF using the ratio of the magnitudes of negative sequence voltage to positive sequence voltage as a fault indicator. This technique is load-independent unlike current-based approaches and employs a fault-detection mechanism for two thresholds, i.e., supply voltage unbalance accounting for ITTFs and single phasing for phase disconnection. In [23], the authors present a method for diagnosing ITTF in traction IMs by injecting a high-frequency (HF) voltage signal into the d-axis and analyzing the extracted HF impedance of the d-axis. This method does not require additional sensors or hardware and can be seamlessly integrated into the existing field-oriented control scheme of induction machines. Another paper presented how to extract fault features from residual xy currents, derived from machine phase currents, without requiring additional sensors for a six-phase IM along with low-pass filters to enhance feature extraction, ensuring robust fault representation under varying operating conditions.

However, the principle is the same as [24]. Second-order positive and negative sequence Park transformation is used to detect and differentiate between ITTF and high-resistance fault (HRF) in SW of permanent magnet machines used for aerospace and rail applications in [25]. It further clarifies that ITTFs appear as DC components in both the second-order positive and negative sequence components, while HRF presents only DC components in the second-order negative sequence components. This discrete feature of ITTF can be employed to distinguish between other types of faults as well.

Table 1. Comparison of ITTF methodologies, advantages and limitation.

Machine Type	Method	Fault Type	Sensor Type	Validation Basis	Advantage	Limitation	Vibration Considered	Proposed Research
IM	Voltage behind reactance	SWITTF	Voltage/Current	Power hardware in loop	Enables fault emulation considering nonlinear leakage inductance	Time consuming analysis	No	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
IM	Clarke Vector Hodograph	SWITTF	Current	Statistical model validated by experimental setup	Offers significant advantage over traditional methods like FFT	Requires complex Signal processing	No	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
IM	Negative sequence current	SWITTF	Current	Finite element method (FEM)	Generates a fault index that increases with fault severity	Depends on DFIG parameters	No	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
IM	Negative sequence voltage	SWITTF	Voltage	Finite element method (FEM) validated by experimental setup	Load independent	Requires voltage Signal processing	No	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
IM	Injecting high frequency voltage	SWITTF	Voltage	Experimental setup	No additional sensors required; integrates with existing FOC	Requires active signal injection	No	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
Permanent Magnet Machines	Second order positive & negative sequence Park transformation	SWITTF	Current	Simulations and experimental testing	Can differentiate between ITTF and high-resistance fault, considers flux density distributions. Model based on vibration current fusion is proposed by using real-time data from distributed control system of turbogenerators for early RW ITTF detection by correlating between current and vibration signals through the gain transformation.	Computational complexity	No	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
Turbogenerator	RW ITTF based on vibration current signal fusion [26]	RWITTF	Rotor Vibration	Simulations and experimental testing	For ITTFs at no load and low load conditions and studies effect of RW ITTF on slot harmonic amplitudes	Does not consider stator ITTFs, lacks consideration FEA/modal behaviour in VA	Yes, partially	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA
IM	Sensitivity of rotor slot harmonics due to ITTF through VA [27]	RWITTF	Rotor slot harmonics and vibration	Simulations and experimental testing		Does not consider stator ITTFs, vibration assessment is incomplete	Yes, partially	Includes both RW & SW ITTF FEA magnetic flux, MA and FFT for possible resonance + stator VA

1.2. Contribution

This paper uses Finite Element Analysis (FEA) modelling which is capable of computing large models with minimal simplifications, required for machine fault modelling [28–30]. In spite of being a time-consuming method of fault analysis, its accuracy is very high compared to conventional voltage, current sensing or Fast Fourier Transformer (FFT)-based fault detection methods. This paper demonstrates the complete coupling by extracting mechanical Maxwell forces under realistic SW and RW ITTFs and presenting how stator and rotor modes are excited with quantitative vibration amplitudes. This study bridges the gap between interdisciplinary subjects, i.e., electrical and mechanical aspects of a DFIG which can be used for CMS of the machine and prevent failures. To understand the implications of the stator and rotor ITTFs, this section provides a standard modelling workflow and novelty of this research in Figure 2. DFIG and its winding arrangement as shown in Figure 3 is studied. Compared to available literature which primarily focuses on current, voltage, flux, or signal processing-based diagnosis of ITTFs, the gap lies in the limited investigation of fault-induced vibration behaviour in DFIGs through a coupled EM structural framework. Existing VA studies generally consider mechanical defects, bearing faults, or partial SW and RW ITTF assessments, while their influence on magnetic flux distribution, modal characteristics, resonance risk, and measurable vibration signatures has not been systematically examined. The unique contribution of this work is the integration of EMT modelling, FEA field analysis, MA, and VA to establish fault-specific vibration signatures for ITTFs, thereby providing a practical vibration-based CMS workflow for DFIG WTUs. The integration for fault-specific DFIG ITTF modal interaction and CMS-oriented vibration indicators is a unique contribution of this paper which lacks in existing research. In the light of Spain and Portugal's power grid failure in April 2025 [31], it is an industrial and a very practical problem to avoid wind farm failures. With increasing dependence on renewable energy in the future, it is critical to update existing old wind farms and design new ones with improved CMS.

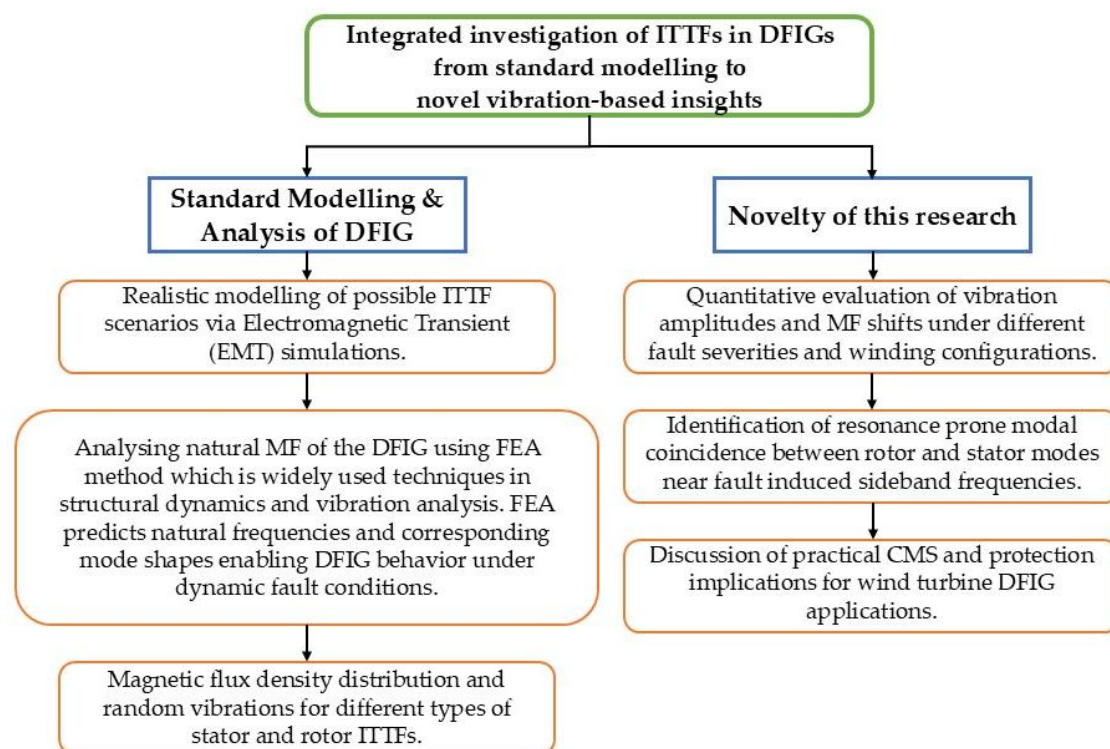


Figure 2. Novelty of this research: Investigation of ITTFs in DFIGs from standard modelling to novel vibration-based insights.

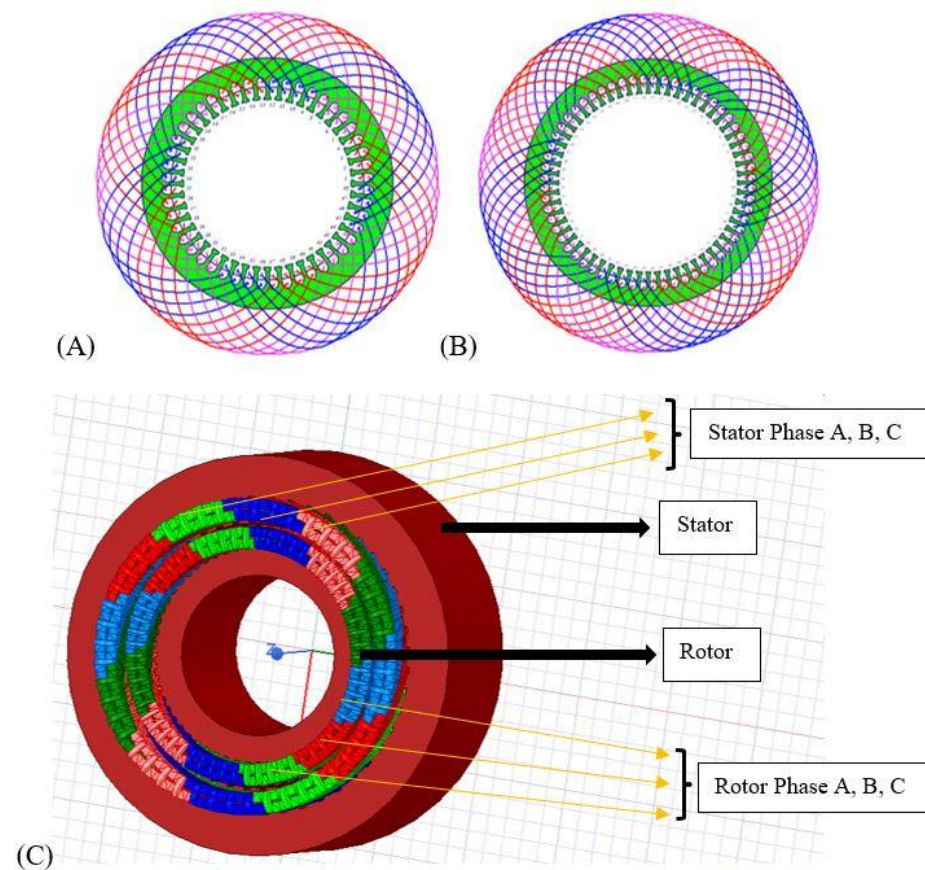


Figure 3. ANSYS Maxwell 2D winding arrangement for a DFIG (A) stator (48 slots) and (B) rotor (60 slots) winding (C) 3D Model of stator and rotor winding arrangement (Phase A—Red, Phase B—Blue, Phase C—Green).

1.3. Wind Turbine Model

In this research, a three-blade, upwind, horizontal-axis WTU with a rotor diameter of 132 m (m) was considered. Its hub height was approximately 94–130 m. The average blade length is 60 m. To keep these blades pointed into the wind, a passive yaw-control system was implemented. It swept an area of nearly 13,000 m² with an average wind speed of 8 m/s at 3 m/s cut in speed and a maximum speed of 25 m/s. The average rotor speed is 7–12 rpm. It was designed as per IEC 61400-22 ed 3, Class IIS/IIIS [1]. However, the turbine has not been modelled in ANSYS Maxwell EMT study and only explained to understand the mechanical behaviour of a WTU.

1.3.1. Wind Turbine Aerodynamics

Equations of wind turbine aerodynamics which evaluate maximum output power from a turbine.

$$P_t = \frac{1}{2} \rho A v^3 C_p(\lambda, \beta) \quad (1)$$

$$C_p(\lambda, \beta) = \frac{1}{2} \left(\lambda - 0.022\beta^2 - 5.6 \right)^{-0.17\lambda} \quad (2)$$

$$\lambda = \frac{r\omega_t}{v} \quad (3)$$

where P_t is the turbine power, ρ is the air mass density, A is the swept area of the rotor, v is the wind speed, C_p is the power coefficient that depends on λ and β , λ is the tip speed ratio, β is the blade/pitch angle, ω_t is the turbine angular speed, and r is the turbine blade radius.

1.3.2. Mechanical System

The mechanical system comprises blades, a gearbox, and a drive train. It evaluates T_{ω_t} i.e., The aerodynamic torque as function of ρ , C_p , v , ω_t , and r is given by Equation (4).

$$T_{\omega_t} = \frac{P_t}{\omega_t} = \frac{1}{2\omega_t} \rho \pi r^2 v^3 C_p(\lambda, \beta) \quad (4)$$

1.4. Doubly Fed Induction Generator

Dynamic modelling of the DFIG expressing the stator flux, rotor flux, stator voltage, and rotor voltage equations in an arbitrary frame of reference rotating at ω speed can be seen from Equations (5) to (9), and the circuit diagram of the d and q axes can be seen in Figure 4. The stator circuit is directly connected to the grid, whereas the rotor windings are connected via slip rings to a three-phase converter. Therefore, the DFIG system can operate in both sub- and super-synchronous modes with a rotor speed range near the synchronous speed. Two level 6 switch back-to-back converters are included in the generator rotor circuit via a capacitor for the DC link, as shown in Figure 4.

$$\psi_s = L_s I_s + L_m I_r \quad (5)$$

$$\psi_r = L_r I_r + L_m I_s \quad (6)$$

$$V_s = R_s I_s + \frac{d}{dt} \psi_s + j\omega \psi_s \quad (7)$$

$$V_r = R_r I_r + \frac{d}{dt} \psi_r + j(\omega - \omega_r) \psi_r \quad (8)$$

$$T_{em} = \frac{3}{2} p (\psi_{qs} i_{ds} - \psi_{ds} i_{qs}) \quad (9)$$

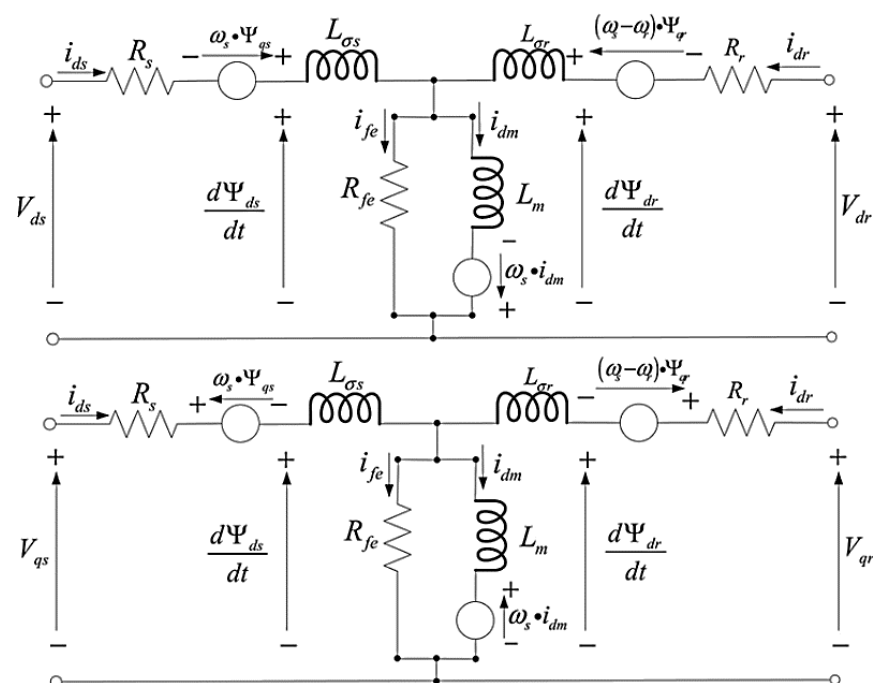


Figure 4. DFIG equivalent circuit.

2. Methodology

The study presented in this paper was divided into two sets of simulations. The DFIG machine was modelled in ANSYS 2022 R2 MAXWELL as per manufacturer's datasheet and

values are provided in Table 2 under the no-load condition and at 22 °C. This operating condition is assumed to study the startup, light-load, or non-operational state as a test condition for a DFIG. MFs and structural deformation patterns are primarily determined by machine geometry, stiffness, and mass distribution, which do not significantly change between no-load and moderate operating conditions. Hence, the selected operating point enables clearer isolation of vibration modes excited by stator and rotor ITTFs and facilitates comparison between healthy and faulty cases. The 22 °C condition represents a standardized ambient reference commonly used in EM modelling to avoid temperature-dependent variations in winding resistance and magnetic properties during the initial fault-characterization stage.

Table 2. DFIG design parameters.

Parameter	Symbol	Value
Rated Power	P_n	2.8 MW
Rated Voltage	V_n	690 V
Pole Pair	p	2
Rated Frequency	f	50 Hz
Nominal Speed	n_s	1500 rpm
Stator Resistance	R_s	0.0009 Ω
Rotor Resistance	R_r	0.007 Ω
Stator Inductance	$L_{\sigma s}$	0.0009 H
Rotor Inductance	$L_{\sigma r}$	0.0009 H
Mutual Inductance	L_m	0.002 H
Rated Torque	T_{em}	19,750 Nm
Number of Stator Slots	-	48
Number of Rotor Slots	-	60
Air gap length	g	3 mm
Rated magnetic flux density	B	2.19 T
Stator dimensions	D	Outer diameter 1060 mm Inner Diameter 700 mm Length 955 mm
Rotor dimensions	d	Outer diameter 693 mm Inner Diameter 425 mm Length 955 mm
Stator Material	-	Steel
Rotor Material	-	Steel
Shaft Material	-	Steel
Winding Material	-	Copper
Copper winding Young's modulus	Y	1.2603×10^5 MPa
Copper Density	kg/m ³	8960
Copper winding Poisson's ratio	-	0.34
Steel Density	kg/m ³	7870
Winding layout	-	Whole coiled
Damping assumption	-	Undamped
B-H curve (Steel 1008)	-	[32]
Stator support condition	-	Fixed
Rotor support condition	-	Remote displacement

The ITTFs in SW and RW were simulated for a low-resistance path in windings of phase A, phase-to-phase AB, and three-phase ABC as presented in Table 3. The 5-turn ITTFs correspond to moderate and 10-turn ITTFs represent severe insulation degradation. It would be rightly assumed that the higher the number of faulty turns, the higher the severity of the fault. As a result, this study considered above mentioned faults for 5- and

10-turn SW ITTFs. As FEA is a time-consuming study, only the case of 5-turn RW ITTFs were simulated as similar trend in outcomes are anticipated.

Table 3. Test cases: elements, location and description.

Case ID	Fault Location	Fault Type	Number of Shorted Turns	Fault Resistance	Short Circuit Path	Severity Level
H	Healthy machine	No fault	—	—	—	Normal operation
SWA5	Stator winding	Single phase A ITTF	5 turns	0.001 Ω	Turn-to-turn within phase A coil	Moderate
SWA10		Single phase A ITTF	10 turns	0.001 Ω		Severe
SWAB5		Phase A to phase B ITTF	5 turns/phase	0.001 Ω	Interturn short between adjacent A and B stator phase coils	Moderate
SWAB10		Phase A to phase B ITTF	10 turns/phase	0.001 Ω		Severe
SWABC5		Three phase ABC ITTF	5 turns/phase	0.001 Ω	Interturn short involving all three phase stator coils	Moderate
SWABC10		Three phase ABC ITTF	10 turns/phase	0.001 Ω		Severe
RWA5	Rotor winding	Single phase A ITTF	5 turns	0.001 Ω	Turn-to-turn within rotor phase A coil	Moderate
RWAB5		Phase A to phase B ITTF	5 turns/phase	0.001 Ω	Interturn short between adjacent rotor phase coils	Moderate
RWABC5		Phase to phase ABC ITTF	5 turns/phase	0.001 Ω	Interturn short involving all rotor phase coils	Moderate

The EMT simulation to present healthy and all faulty cases was performed using the ANSYS EMT tool. The EMT analysis with a step size of 0.1 ms shows the currents in the SW in all scenarios simulated for 1.25 s by Backward Euler method. Selection of time step comes from Equation (10), where f_s is the grid frequency, i.e., 50 Hz. So, it should be a minimum of 1 ms, for higher accuracy 0.1 ms has been chosen.

$$\text{Step size} \leq \frac{1}{20 \times f_s} \quad (10)$$

The nonlinear solver convergence criterion was based on magnetic-energy residual reduction with a tolerance of 10^{-4} between successive iterations. FFT of EMT based stator currents for SW ITTFs and RW ITTFs is performed in MATLAB 2021b with sampling frequency of 10 kHz and sampling period of 0.1 ms. A Hann window was applied to the steady-state EMT stator current waveform prior to FFT computation and sideband components were extracted around the fundamental grid frequency 50 Hz and the identified MF.

MA is solved using 44,196 elements and almost 250,000 nodes. This fine mesh configuration was selected for all reported simulations to ensure numerical accuracy while maintaining acceptable computational cost. This fine mesh size was automatically determined by Workbench meshing algorithm based on the selected fine mesh sizing and geometric characteristics of the model. However, no mesh-independence study was performed. The second objective of this study is to analyze the DFIG machine in ANSYS Workbench and present a comparison between various vibration modes occurring as a consequence of ITTFs dwelling in the SWs and RWs. The VA of the machine is influenced by various aspects that originate from both the mechanical and electrical design factors of the machine.

A one-way coupling approach between EMT and Workbench is adopted as resulting structural deformations are sufficiently small, and therefore, their feedback effect on the

EM field distribution is considered negligible. EM loading responsible for radial machine vibration was extracted from EMT-based MAXWELL simulations for healthy and faulty operating conditions by force distribution over the relevant machine surfaces. The obtained EM excitation was then transferred to the structural model developed in Workbench and applied on the corresponding stator and rotor regions exposed to magnetic loading. Since EM and structural discretisation are not identical, EM loading was carried out through spatial mapping between the Maxwell and Workbench meshes to obtain natural frequencies and mode shapes from MA. No additional empirical scaling factor was introduced during transfer, so the structural loads correspond directly to the EM excitation calculated for each operating condition. Mathematically, stator and rotor MFs were assessed with respect to the natural frequencies and to evaluate resonance risk. Consequently, VA was performed only on stator assembly as it exhibits significantly higher deformation magnitudes and vibration amplitudes. Due to the stator's larger, hollow geometry and fixed-frame mounting, it possesses lower relative stiffness for certain modes, making it the primary component of concern for mechanical failure during severe faults. This integration of EMT modelling, FEA field analysis, MA, and VA to establish fault-specific vibration signatures for ITTFs for a practical vibration-based CMS workflow has been implemented. It should be noted, confirmation of CMS indicators under loaded/hot operating conditions have not been considered and are necessary in the future. The results are presented in Section 3.

3. Results

The steady-state performance of the 2.8 MW DFIG under healthy and ITTFs is performed at no load and 22 °C conditions. Healthy DFIG torque vs. speed, efficiency vs. speed, stator and rotor currents vs. slip, and power vs. slip plots produced via ANSYS Maxwell EMT simulations are presented below in Figure 5. When SW and RW ITTFs are introduced, the balanced EM symmetry of the machine is disrupted. The EMT analysis reveals that ITTFs lead to significant phase current imbalances and increased peak magnitudes in the SWs. The severity of this distortion is directly proportional to number of shorted turns and the number of faulted phases. RW ITTFs manifest as visible distortions and sideband components in the stator current waveforms, confirming that rotor insulation degradation is observable through stator-side monitoring due to the EM coupling across the air gap. The current signatures for the healthy, SW ITTFs and RW ITTFs operating scenarios are detailed in Figure 6.

EM FEA computes magnetic vector potential ($\bar{A}$) such that the curl of $\bar{A}$ is the magnetic flux density vector ($\bar{B}$) as seen in Equation (11);

$$\nabla \times \bar{A} = \bar{B} \quad (11)$$

Ampère's law similarly relates the magnetic field strength vector ($\bar{H}$) and current density vector as seen in Equation (12);

$$\nabla \times \bar{H} = \bar{J} \quad (12)$$

Substituting $B = \mu H$, and assuming μ is constant, the following Equation (13) provides the direct relation between B and J . However, in the actual FEA simulations performed in ANSYS Maxwell, nonlinear magnetic material behaviour is considered using the built-in nonlinear B–H curve model of the electrical steel core material. Therefore, permeability is not treated as constant during computation.

$$\nabla \times \bar{B} = \mu \bar{J} \quad (13)$$

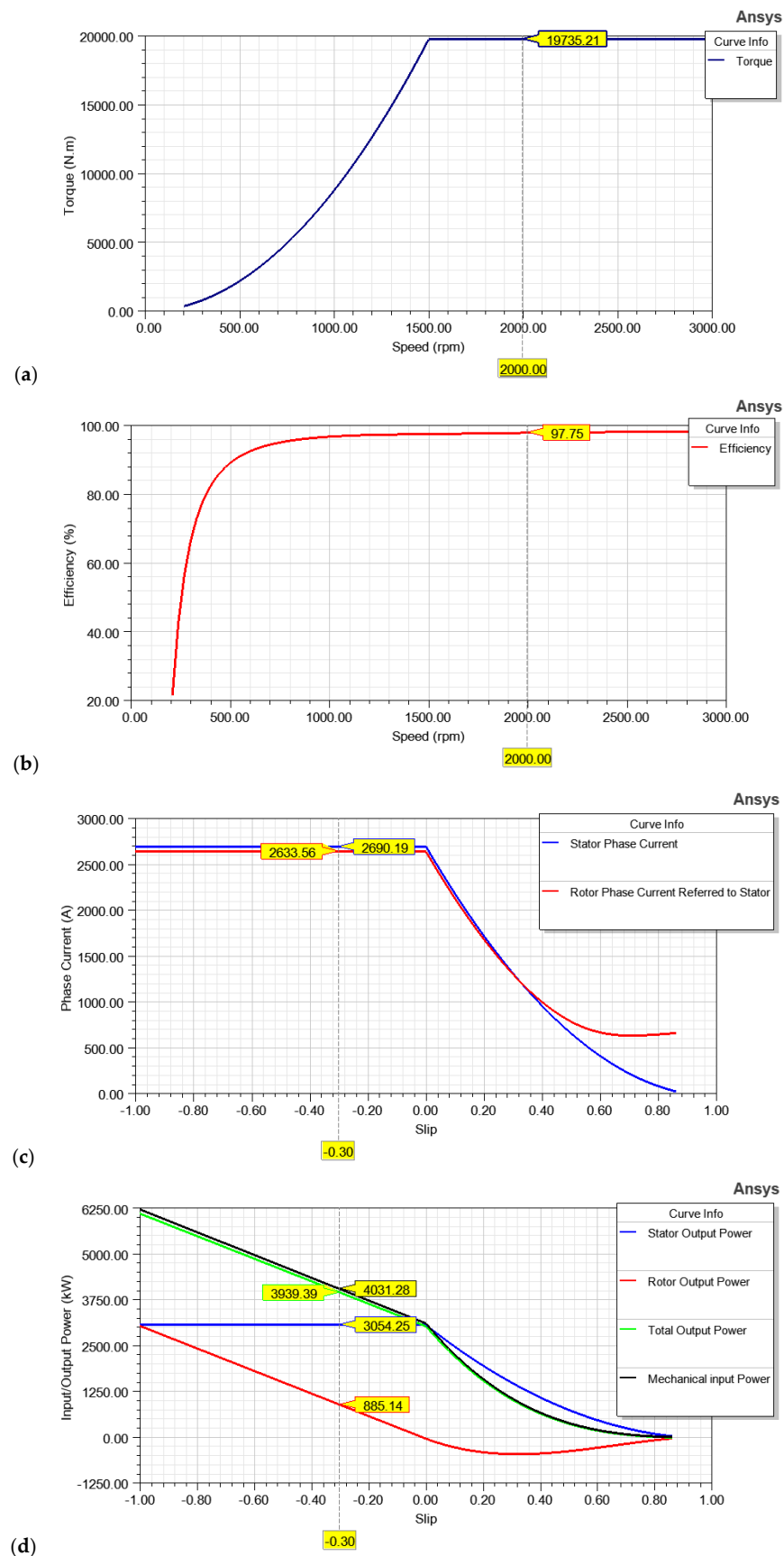


Figure 5. Performance charts of DFIG under analysis (a) Output torque (kNm) vs. speed (rpm) (b) Efficiency % vs. speed (rpm) (c) Stator and Rotor phase currents (Amp) vs. Slip (d) Power (kW) vs. Slip.

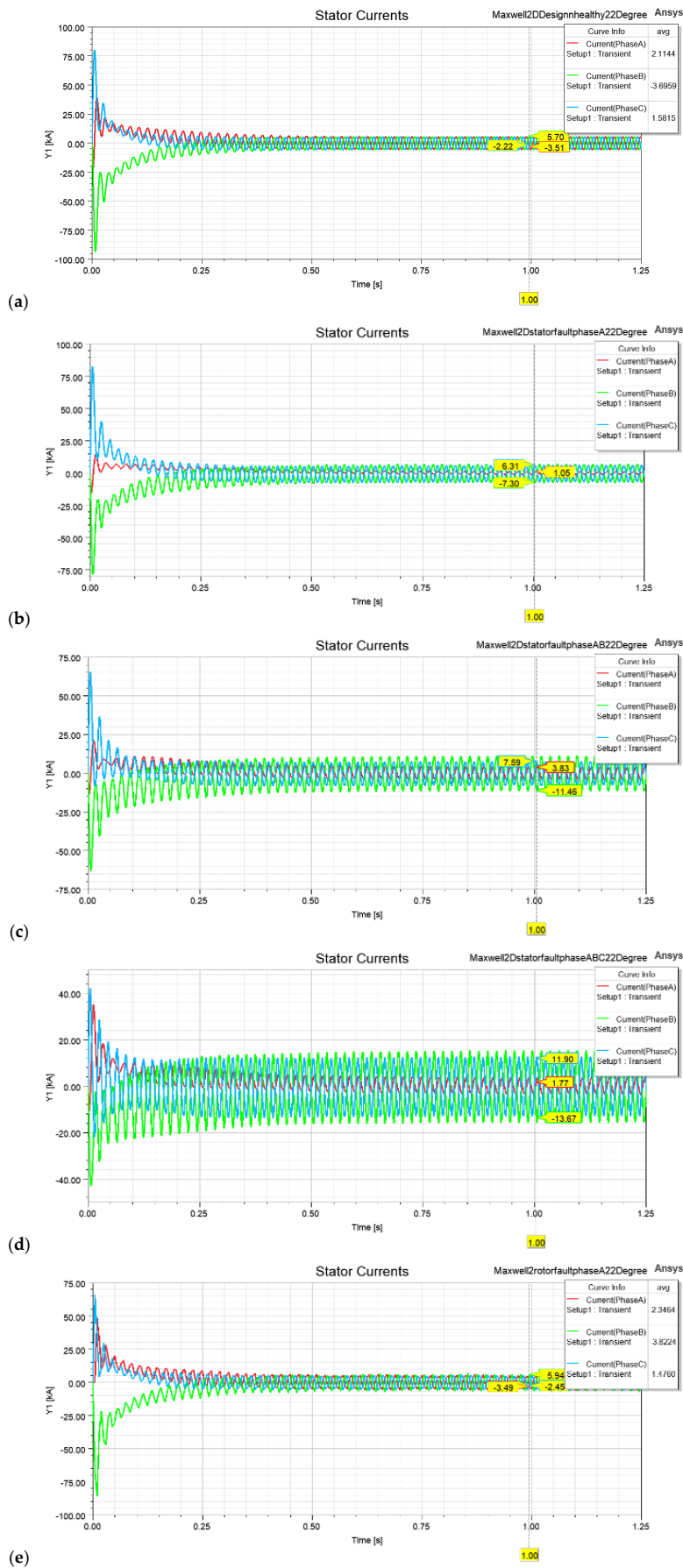


Figure 6. Cont.

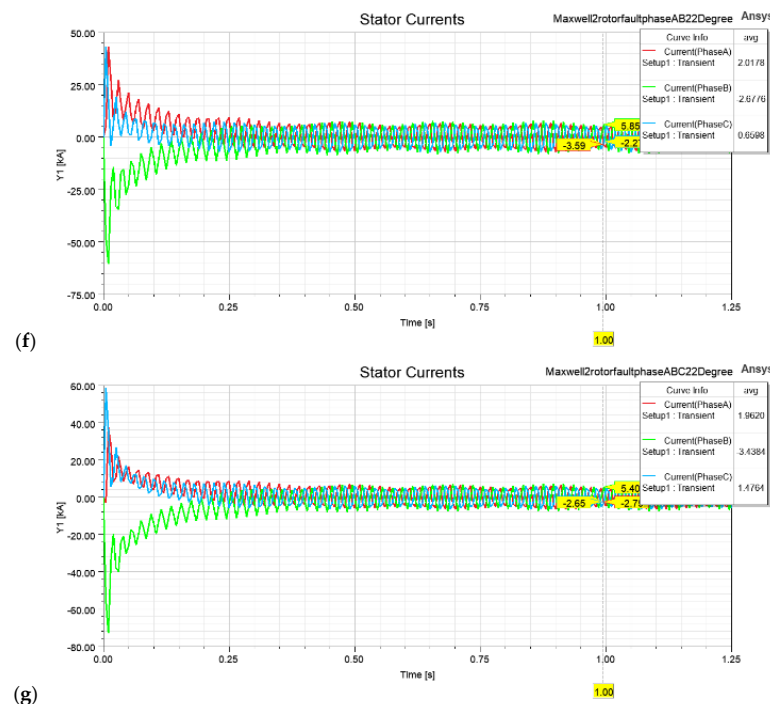


Figure 6. Stator current for (a) H, (b) SWA, (c) SWAB, (d) SWABC, (e) RWA, (f) RWAB, (g) RWABC.

Figure 7 presents the simulated $\vec{B}$, that is, the measure of strength and direction of the magnetic field, expressed in Tesla for a healthy machine in Figure 7a with a max B of 2.3278 T which is ideally the linear operation region of BH curve against the rated value of 2.19 T. For a SWA ITTF in Figure 7b with Max B of 4.1997 T close to the fault location, SWAB ITTF in Figure 7c with Max B of 4.3241 T near the fault location, and SWABC ITTF in Figure 7d with Max B of 4.266 T near the faulted end-windings. For a RWA ITTF in Figure 7e with a Max B of 4.2575 T, RWAB ITTF in Figure 7f with a Max B of 4.2772 T, and RWABC ITTF in Figure 7g with a Max B of 4.3993 T. The higher the $\vec{B}$ close to fault location, the higher is the fault current as understood from Equations (11) to (13) and consequently the higher the stress on the winding insulation. This can be precarious for the DFIG if such a stress on the insulation is sustained for a long time. From the above discussion it can be understood that the end-windings locally exceed linear operation and enter the typical knee region and even saturation region during ITTFs. $\vec{B}$ field distortions over the knee region can create local hot spots.

The safe limit of $\vec{B}$ is typically up to ~2 T depending on material properties that can be dangerous if the fault current increases or fault spreads out further as seen in [33]. Stator and rotor material being steel in this case has a magnetic saturation knee point around ~2.1 T [32]. The known literature shows similar localized $\vec{B}$ for smaller power rating generators to be about ~2.4 T [34,35]. Localized over-fluxing phenomena have been reported in FEA investigations of SW ITTFs, where fault-induced magnetic hotspots substantially exceed the nominal operating flux density while remaining confined to a small spatial region. Numerical stability at such high B does not seem to be compromised because it is very localized to fault and does not seem to spread in a wider region. On comparing with published experimental data and high-fidelity simulation studies, it seems like a typical outcome [36,37]. It should be implicitly realized that these are localized numerical peak values near the fault region and sensitive to mesh resolution and nonlinear modelling of stator and rotor materials.

The vibration caused by an external force, $F(t)$, imposed on a system can be mathematically described as

$$M \frac{d^2 U}{dt^2} + C \frac{dU}{dt} + K(u)t = F(t) \quad (14)$$

where M , C , and K are the mass, damping, and stiffness matrices, respectively, of the system. $\frac{d^2 U}{dt^2}$, $\frac{dU}{dt}$ and $(u)t$ are respectively the acceleration, velocity, and displacement of each element of the system. MA based on the nondamped free vibration of the system is as follows:

$$M \frac{d^2 U}{dt^2} + K(u)t = 0 \quad (15)$$

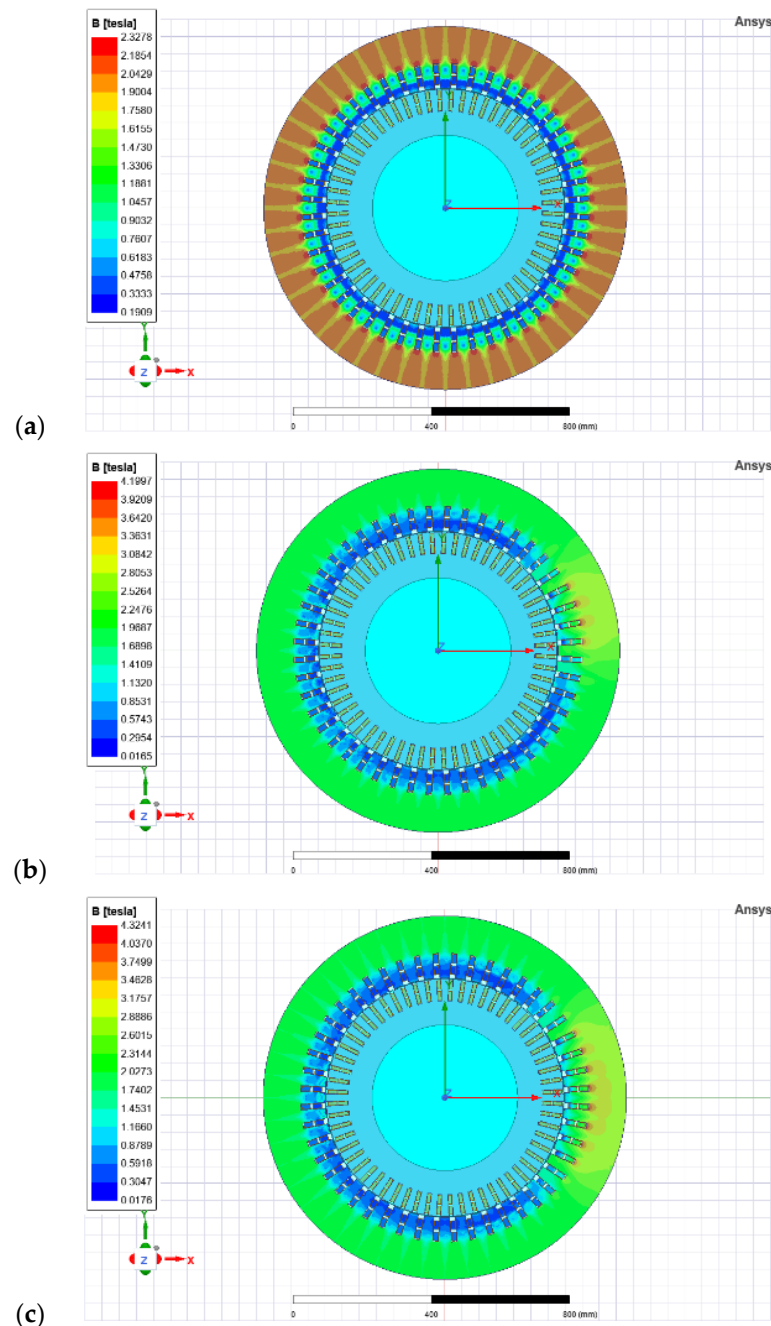


Figure 7. Cont.

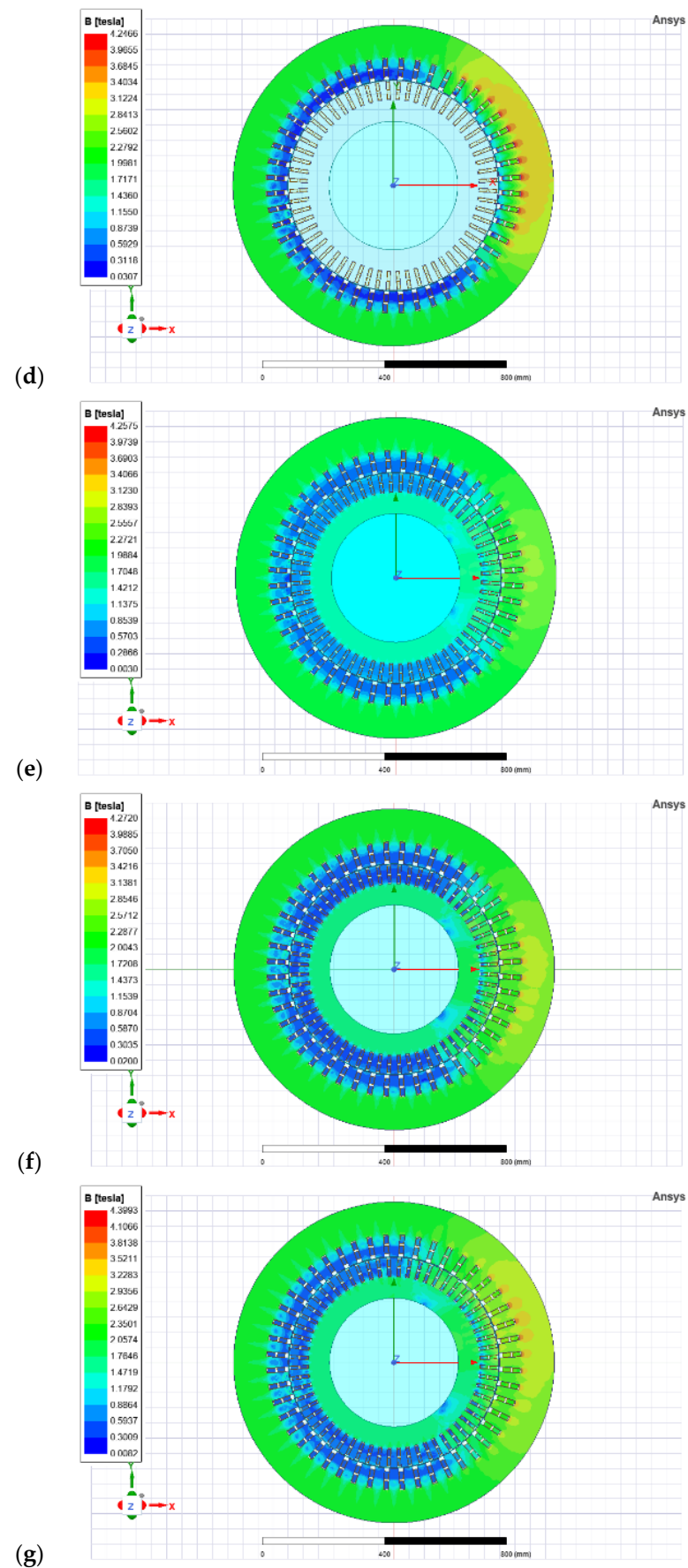


Figure 7. Magnetic flux density (B) in Tesla for (a) H, (b) SWA, (c) SWAB, (d) SWABC, (e) RWA, (f) RWAB, (g) RWABC.

Vibrations within the electrical machine are produced at the same frequencies but different amplitudes for each element, that is,

$$(u)t = \varphi \sin(\omega t + \phi) \quad (16)$$

$$([K] - \omega^2[M])\varphi = 0 \quad (17)$$

where the eigenvalues ω and mode shapes φ can then be obtained. These calculations were performed internally using the ANSYS 2022 R2 MA tool. In this study, undamped MA is adopted as the primary objective to identify natural frequencies and mode shapes associated with SW and RW ITTFs. Undamped formulation provides sufficient accuracy to identify fault-sensitive vibration modes and potential resonance conditions.

Table 4 below tabulates rotor and stator ITTFs and their first 25 MFs which are then plotted in Figures 8 and 9.

Table 4. First 25 Natural Modal frequencies of Rotor and Stator healthy vs. during ITTF in Phase A, AB & ABC.

Mode	Healthy Stator	SWA5	SWA10	SWAB5	SWAB10	SWABC5	SWABC10	Healthy Rotor	RWA5	RWAB5	RWABC 5
1	0	0	0	0	0	0	0	0.000	0.000	0.000	0.000
2	0.000	0.001	0.011	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000
3	0.012	0.010	0.017	0.012	0.007	0.008	0.028	0.003	0.002	0.003	0.003
4	62.337	62.434	62.334	62.333	62.339	62.355	62.333	37.34	36.80	36.17	35.47
5	62.367	62.799	62.378	62.369	62.372	62.496	62.368	65.52	63.60	61.95	60.69
6	99.594	100.77	101.04	99.59	99.593	99.588	99.586	65.57	64.76	64.25	63.50
7	454.39	258.78	452.58	454.05	451.71	452.73	452.94	426.29	410.06	410.09	409.99
8	455.4	324.24	454.77	455.09	454.4	454.3	454.81	532.72	426.45	426.46	426.49
9	457.39	342.29	456.85	456.52	454.98	456.51	455.34	540.11	531.38	534.18	534.20
10	457.96	369.57	458.77	457.46	457.99	457.66	457.37	551.15	540.66	538.99	535.77
11	475.48	372.35	474.01	475.61	473.81	474.2	474.78	554.45	546.21	550.97	553.99
12	477.47	403.78	475.86	476.91	474.61	475.22	475.83	561.25	556.66	558.40	556.70
13	478.2	416.49	476.59	477.17	475.36	476.14	476.86	570.00	564.60	569.13	571.19
14	478.57	428.03	477.62	478.25	475.85	477.69	477.5	574.29	574.30	574.10	580.05
15	479.02	438.5	479.05	479.38	477.18	478.93	478.86	577.66	579.26	587.11	591.32
16	481.45	446.52	480	481.08	478.01	479.73	479.46	587.39	591.48	591.41	597.08
17	482.03	468.35	480.91	481.28	479.21	480.39	480.6	598.81	593.88	603.88	612.68
18	482.54	472.17	482.35	482.34	480.93	481.53	481.66	608.54	608.05	616.23	626.19
19	484.02	477.53	484.29	483.36	482.34	483.66	482.82	615.80	618.54	626.57	626.49
20	485.7	479.68	486.97	486.04	485.41	484.52	484.19	624.65	626.61	628.65	636.85
21	487.98	483.19	489.2	487.32	486.81	488.04	487.8	631.45	629.22	637.58	642.40
22	488.99	485.84	491.23	487.55	488.41	488.69	489.44	636.78	637.26	643.02	646.34
23	495.79	487.68	492.91	493.89	491.71	491.24	491.86	639.94	641.64	646.50	650.68
24	496.14	490.82	493.37	494.59	492.12	492.13	493.05	644.34	645.23	650.77	653.65
25	501.81	493.03	500.99	501.38	499.09	499.98	500.2	646.92	650.51	653.09	655.80

Figure 8 shows the deformations of different vibration modes at different frequencies for the healthy stator in (a). The 1st mode appears at 62.337 Hz, 2nd significant mode at 99.5 Hz, and then above 454 Hz. A high-deformation case is observed at higher modes at, for example, 606 Hz. Whereas, for SWA ITTF in (b), 1st mode appears at 62.434 Hz, 2nd significant mode at 100.7 Hz, and then at 258.78 Hz. A high-deformation case was observed at higher modes at 416 Hz. For SWAB ITTF in (c), 1st mode appears similarly at 62.434 Hz, 2nd significant mode appears at approximately 99 Hz, and then at approximately 450 Hz. A high-deformation case was observed at higher modes over 455 Hz and 615 Hz. A similar trend was observed in SWABC ITTF in (d). The presented modes are for five faulty turns of SW. If the stator deformation is too high and the clearance with the rotor is small, there is a risk of contact for a transient event or resonance. Vibration modes over 400 Hz can be excited by current harmonics.

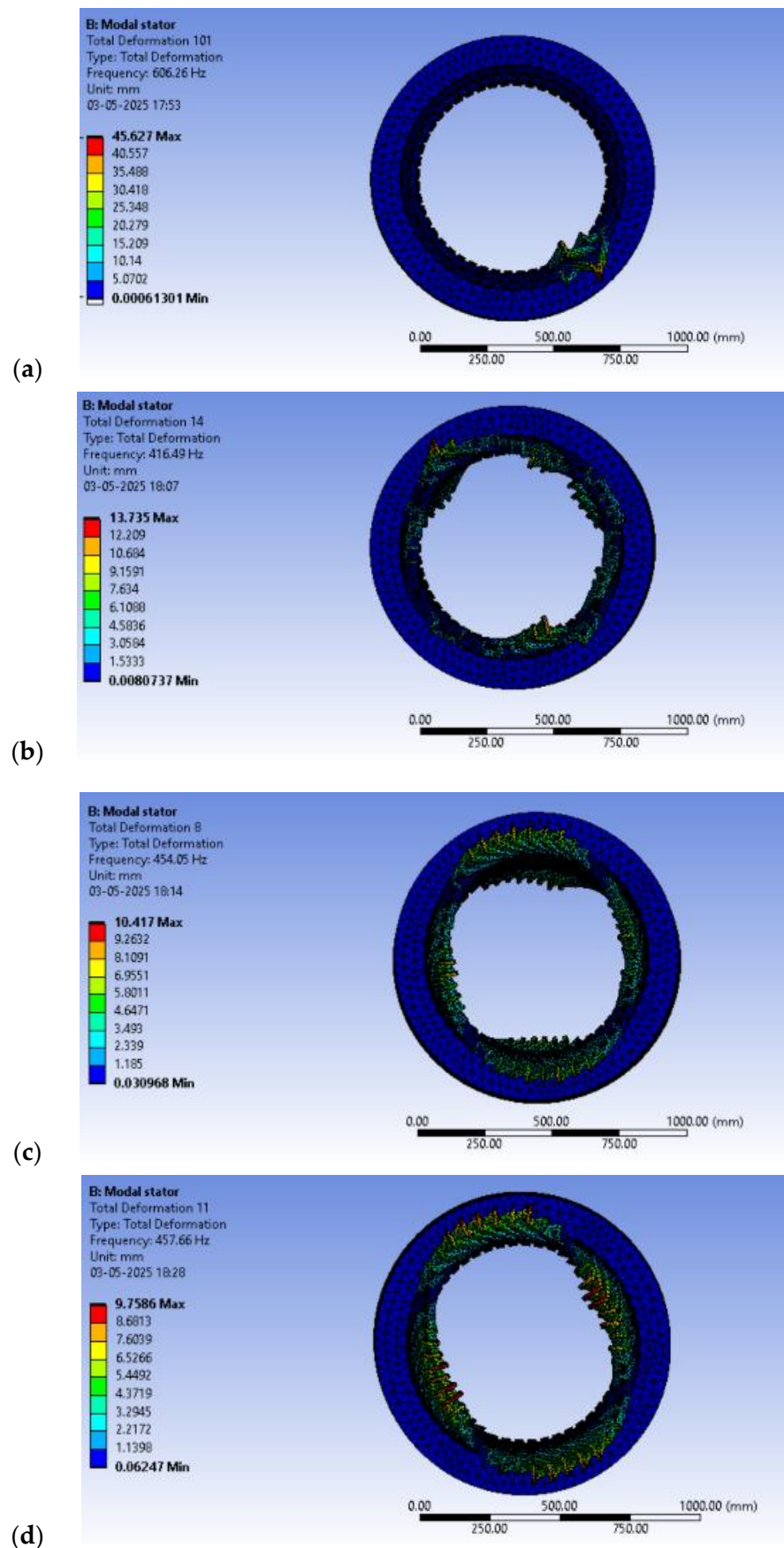


Figure 8. Modes of frequency for (a) healthy stator, (b) SWA, (c) SWAB (d) SWABC.

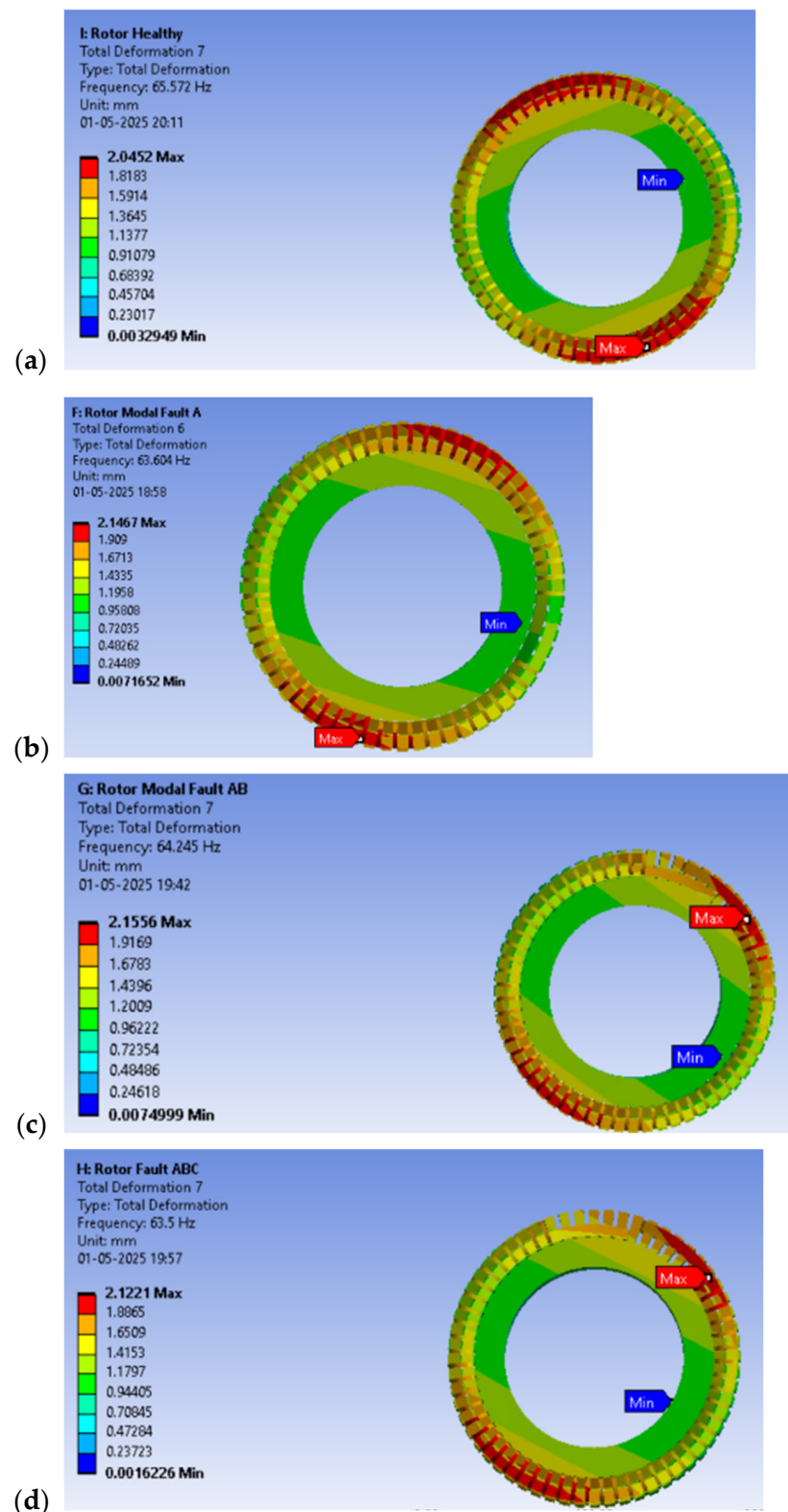


Figure 9. Modes of frequency for (a) Healthy rotor (b) RWA (c) RWAB (d) RWABC.

Figure 9 shows the deformation for different vibration modes at different frequencies for a healthy rotor in (a). The 1st mode appears at approximately 37 Hz, 2nd significant mode appeared at approximately 65 Hz, and then above 426 Hz. For RWA ITTF in (b), 1st mode appears at approximately 36.8 Hz, 2nd significant mode appears at 63 Hz, and then at 410 Hz. For RWAB ITTF in (c), 1st mode appears similarly at 36.1 Hz, 2nd significant mode appears at approximately 62 Hz, and then at around 410 Hz, 425 Hz, and higher. A similar

trend was observed for RWABC ITTF in (d). The presented modes are five faulty turns in RWs. Overall, rotor deformations are not as high in magnitude as stator deformations owing to differences in build and design. As the stator is a larger body than the rotor, is hollow and fixed to the frame, it allows less stiffness for some modes. The rotor mass distribution was more balanced and symmetrical.

However, it can be seen from Figure 10 that a few modes of vibration of the stator and rotor are at very close frequencies, which increases the risk of resonance and coupled vibration. For example, 4th and 5th mode of the SW and 5th and 6th mode of the RW are very close to 62 Hz. This could lead to potential instability owing to self-excited vibrations, as calculated in Equations (18)–(24). It is also observed that in the 5th rotor mode MF decreased to 63.604 Hz under RWA ITTF compared to 65.521 Hz in the healthy condition, corresponding to a MF shift of approximately 1.917 Hz. Similarly, the 4th rotor mode shifted by approximately 0.53 Hz, while the stator modes exhibited smaller positive shifts ranging between 0.018 and 0.5 Hz. In addition, the moving current sidebands produced by rotor and stator interactions commonly appear as follows:

$$\text{Uppersideband : } f_{up} = f_s + sf_s = (1 + s)f_s \quad (18)$$

$$\text{Lowersideband : } f_{low} = f_s - sf_s = (1 - s)f_s \quad (19)$$

where f_s = grid the grid/stator frequency, that is, 50 Hz, and $sf_s = f_r$ = rotor frequency in Hz.

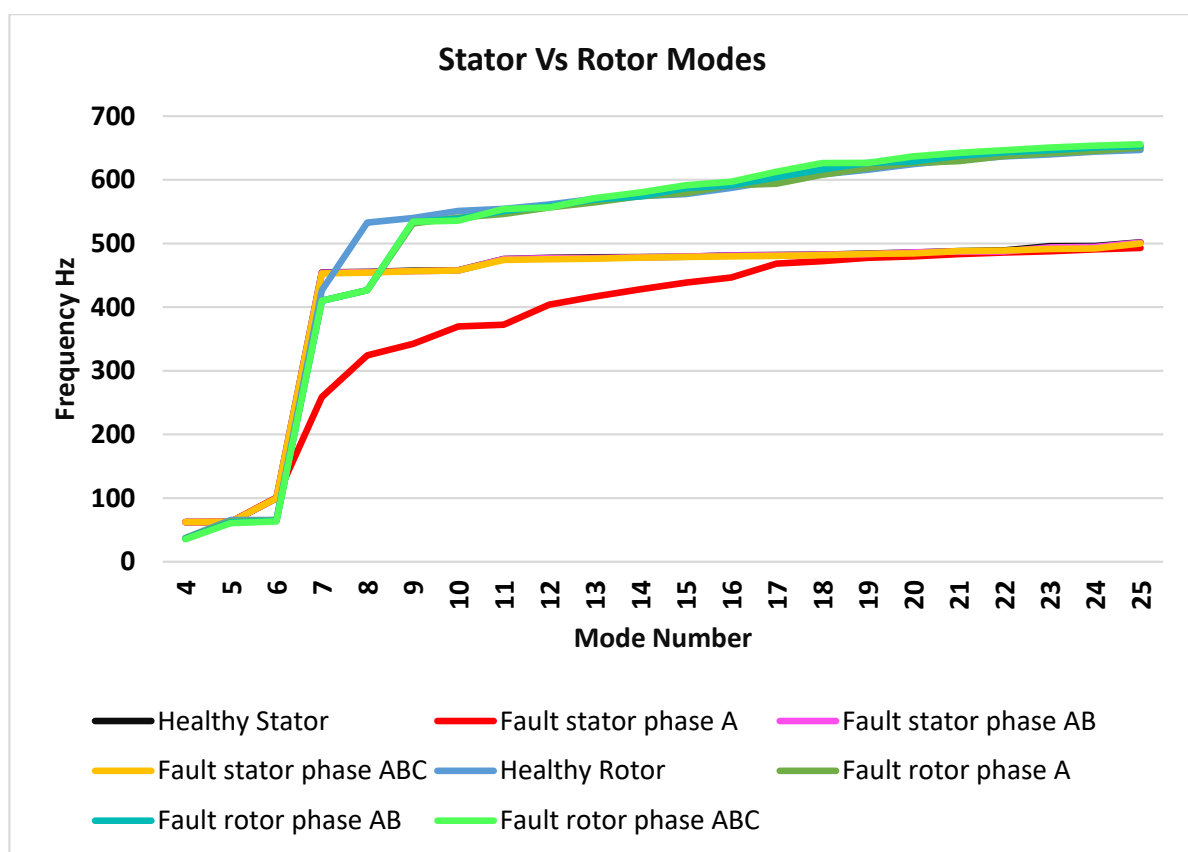


Figure 10. Stator vs. Rotor modes (up to 1st 25 modes).

Given a target frequency, f_t i.e., a MF of ~ 62 Hz, the rotor speed n_r (rpm), where the sideband is equal to

$$f_t = f_s \pm sf_s \quad (20)$$

Solving slip s_{up} for upper sideband:

$$s_{up} = f_t / f_s - 1 \quad (21)$$

And rotor speed for upper sideband:

$$n_{r-up} = n(1 - s_{up}) = n(2 - f_t / f_s) \quad (22)$$

Solving slip s_{low} for lower sideband:

$$s_{low} = 1 - f_t / f_s \quad (23)$$

And rotor speed for lower sideband:

$$n_{r-low} = n(1 - s_{low}) = n(f_t / f_s) \quad (24)$$

For $f_t = 62$ Hz, $n_{r-up} = 1140$ rpm and $n_{r-low} = 1860$ rpm. If the generator speed is approximately 1050–1140 rpm, the moving upper sideband will coincide with the ~ 62 Hz modal band, and if an ITTF increases the sideband amplitude, a strong excitation of 2nd mode of the rotor can occur with 1st mode of the stator.

The above calculated speed range of approximately 1050–1140 rpm thus remains operationally relevant since it may occur intermittently during a practical WTU operation. In contrast, the super-synchronous speed near 1860 rpm is less likely to occur continuously in commercial DFIG WTUs and mainly represents a theoretical resonance condition identified through the sideband analysis. This can be understood from the cut-out wind speed of 25 m/s [1], and provided gear ratio of 111 by NGC Gear FDM2F [38] providing a generator speed between 821.4 rpm to 1724 rpm for a 50 Hz grid operation. Enhanced monitoring may be useful for this speed range, but it does not imply to be a unique ITTF indicator. Consequently, the sub-synchronous resonance region is considered more practically significant for CMS and protection system implementation in DFIG WTUs.

Figure 11 presents a comparison of the modes of vibration vs. frequency in Hz for a healthy stator vs. SWA ITTF, SWAB ITTF, SWABC ITTF with five winding turns in (a) and between the healthy stator and SWA ITTF, SWAB ITTF, SWABC ITTF with 10 winding turns in (b). It is evident that even for higher modes, the single-phase fault case has a higher frequency during vibration compared with all other cases. In Figure 11c, the modes of vibration for the healthy rotor vs. RWA ITTF, RWAB ITTF, RWABC ITTF with five winding turns are shown.

Table 5 below summarizes rotor and stator mode shapes to compare key MFs for RW and SW ITTFs with healthy DFIG. This has been tabulated for selected frequencies up to 100 Hz as they are closest to system frequency of 50 Hz. Further to that, Figure 12 provides FFT of stator current for (a) Healthy machine (b) SWA, (c) SWAB, (d) SWABC, (e) RWA, (f) RWAB, and (g) RWABC. FFT analysis in Figure 12 demonstrated that both stator and rotor ITTF conditions introduced increased sideband amplitudes compared with the healthy baseline, particularly in the frequency region near the identified structural modes around 62 Hz. Multi-phase and higher turn fault cases exhibited the largest spectral amplification, indicating stronger EM excitation of the structural modes. The proximity between the dominant fault-induced sideband components and the identified rotor and stator MFs suggest increased susceptibility to resonance-related vibration amplification and electromechanical coupling under ITTF conditions. In particular, the 2nd rotor mode and 1st stator mode exhibited close modal interaction within the same frequency band, indicating a resonance-prone operating region relevant for CMS.

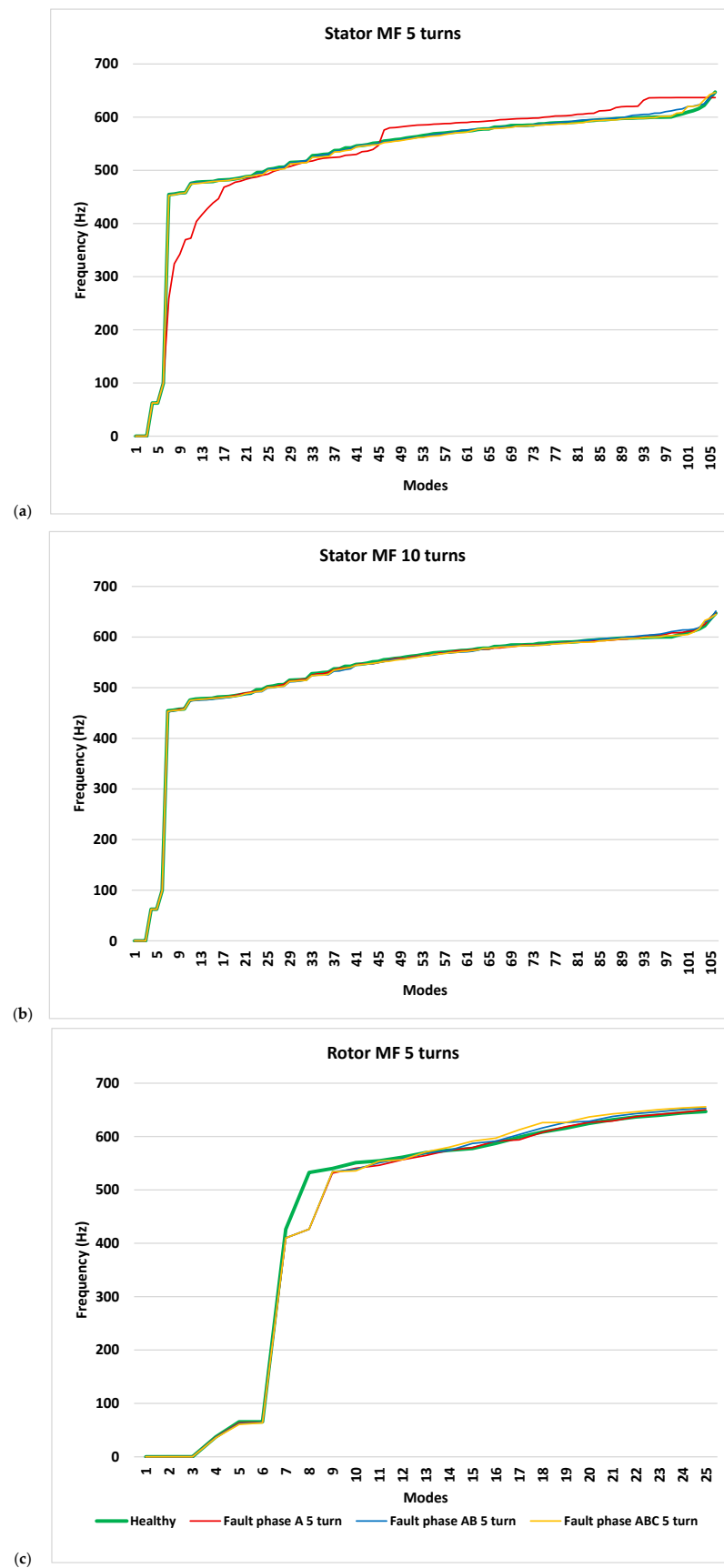


Figure 11. Frequency in Hz vs. Modes of vibration (a) healthy stator vs. SWA5, SWAB5, SWABC5 (b) healthy stator vs. SWA10, SWAB10, SWABC10 (c) healthy rotor vs. RWA5, RWAB5, RWABC5.

Table 5. Selected modal frequencies for rotor and stator and their frequency shift and mode shapes.

Mode	Structure	Healthy Frequency (Hz)	Fault Phase A Frequency (Hz)	Frequency Shift (%)	Normalized Deformation	Dominant Mode Shape
4	Rotor	37.336	36.802	−1.43%	0.0023	Global radial bending
5	Rotor	65.521	63.604	−2.93%	0.0028	Ovalization mode
6	Rotor	65.572	64.755	−1.25%	0.0029	Coupled radial mode
4	Stator	62.337	62.434	+0.16%	0.0095	Circumferential breathing
5	Stator	62.367	62.799	+0.69%	0.0169	Ovalization mode
6	Stator	99.594	100.77	+1.18%	0.0280	Tooth deformation mode

It can be clearly seen in Figure 13 that, out of all three types of faults, a single-phase fault has a maximum VA of 2116 mm/s at 480 Hz for a higher number of faulty turns. In contrast, SWAB ITTFs have higher vibration amplitude than SWABC ITTFs. This can be explained by the fault severity increasing due to increasing turns as well. Single-phase faults are localized, and shorted turns form a low-impedance path, leading to a higher circulating current and a lack of balance of the fault current. On the other hand, three-phase faults rarely occur, have a lower magnitude, and lead to a symmetrical high current that is not higher than the initial SC current of a single-phase fault. However, as mentioned above there are no considerations of damping in this study, so a high vibration of 2116 mm/s is observed. It should be noted that this value as a numerical undamped indicator rather than a physically validated vibration velocity as ISO 10816-3 limits generators with power capacity above 300 kW must be a maximum of 4.5 mm/s for unrestricted operation, and with a VA up to 11 mm/s, severe damage can occur [39]. It may be realized that introduction of damping in the rotor and stator windings with parallel paths can reduce this vibration [40]. It should be noted, Figure 13 focuses on the stator due to its hollow, fixed geometry manifesting lower stiffness and making it the primary component of concern for mechanical failure during severe faults. Equivalent rotor vibration assessment is a limitation of this study due to computational time and costs.

Figure 12 and Table 6 below quantitatively demonstrate the increase in fault-induced sideband amplitudes near the 62 Hz modal band relative to the healthy machine, thereby supporting the proposed electromechanical modal interaction mechanism. Sideband components were extracted around the fundamental grid frequency 50 Hz and the identified modal interaction band ~62 Hz. Table 6 is produced by calculating the % difference in FFT sideband amplitude (A) in dB for healthy ($A_{healthy}$) and ITTF case in SW and RW (A_{faulty}) near 62 Hz modal band as per following Equation (25) and normalization as presented in Equations (26) and (27).

$$\% \text{ difference} = \frac{A_{faulty} - A_{healthy}}{A_{healthy}} \times 100 \quad (25)$$

$$A_{healthy} \text{ dB} = 20 \log_{10}(A_{healthy}) \quad (26)$$

$$A_{faulty} \text{ dB} = 20 \log_{10}(A_{faulty}) \quad (27)$$

Table 6. Comparison of machine conditions for dominant sideband and FFT.

Condition	Dominant Sideband Frequency (Hz)	FFT Amplitude (dB)	Increase vs. Healthy (%)	Closest Structural Mode
Healthy	50.0	0.08	Not applicable	No coincidence
SWA	61.8	0.19	+137%	1st stator mode
SWAB	62.1	0.31	+287%	1st stator mode
RWA	62.0	0.27	+237%	2nd rotor mode
RWABC	62.3	0.42	+425%	Rotor–stator modal coincidence

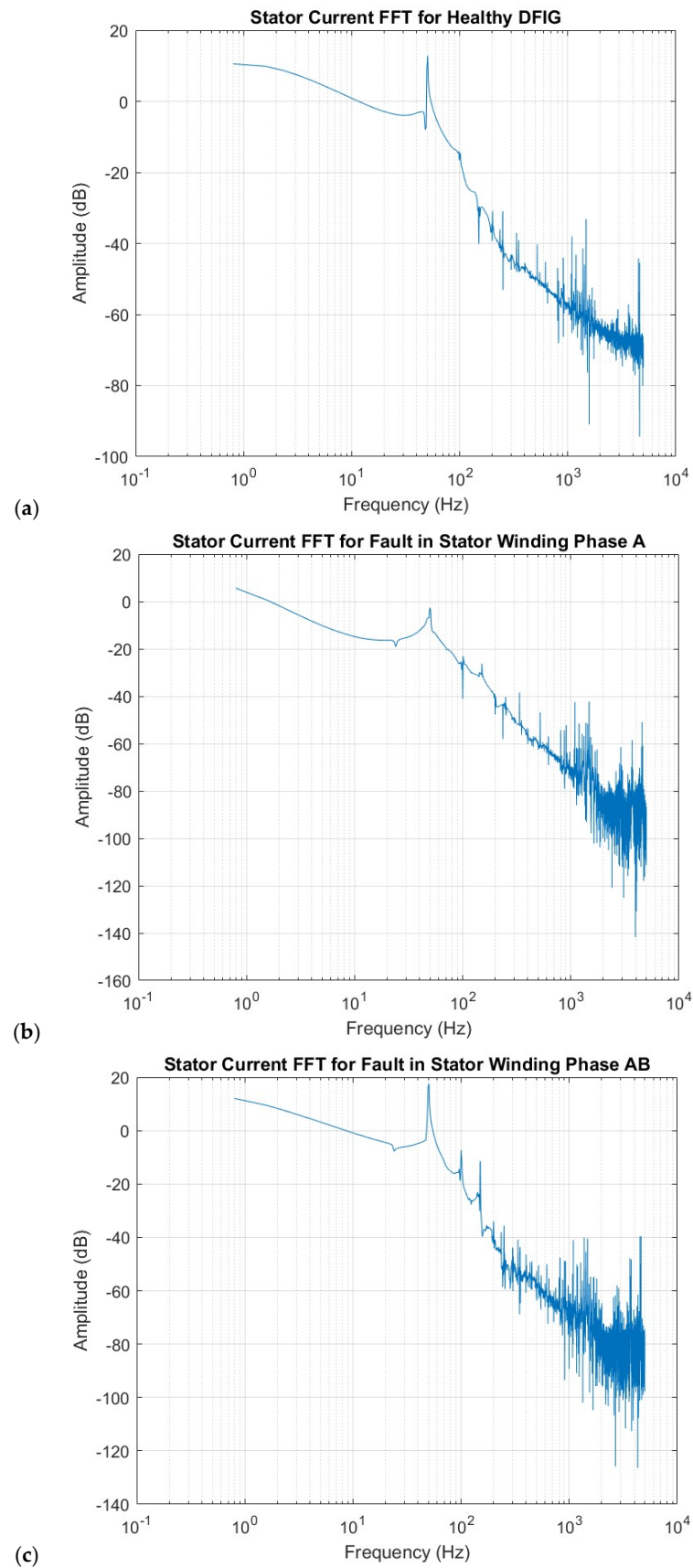


Figure 12. Cont.

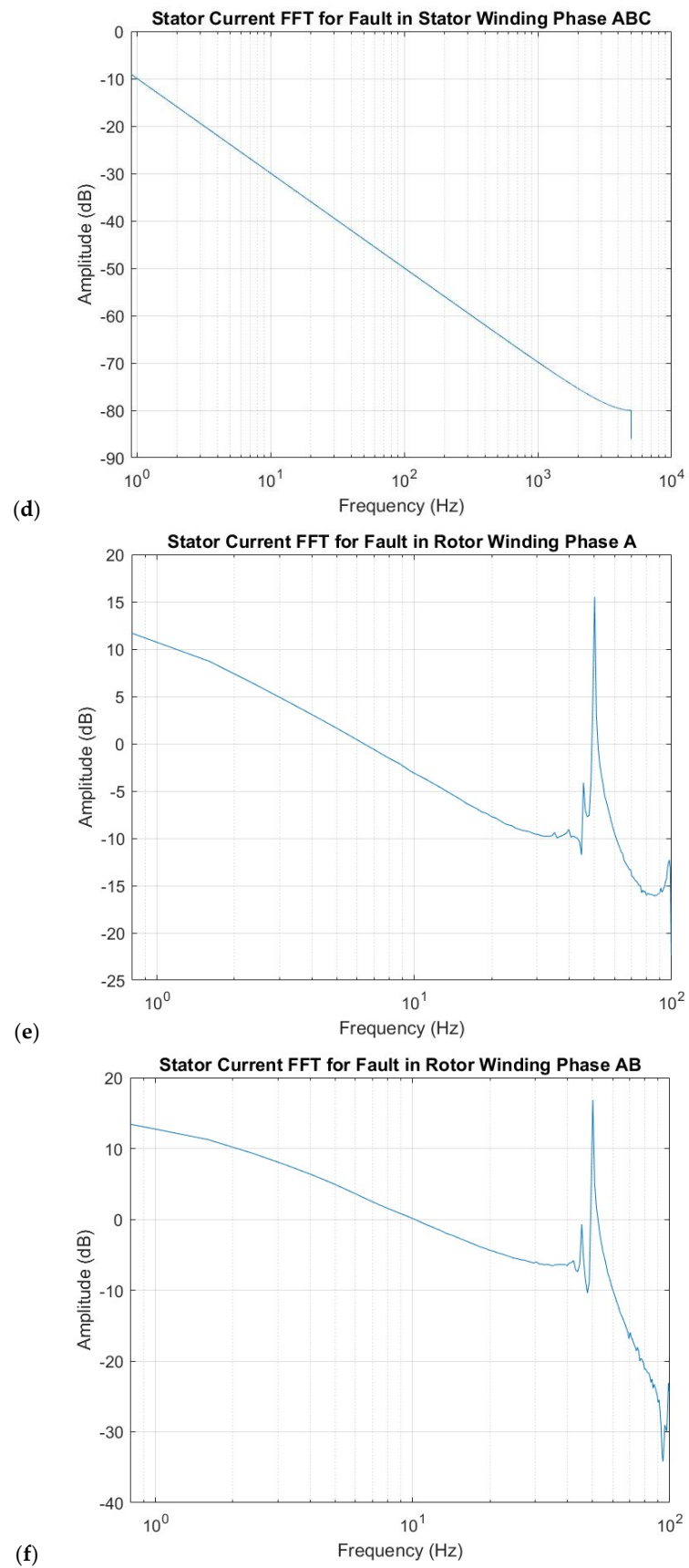


Figure 12. Cont.

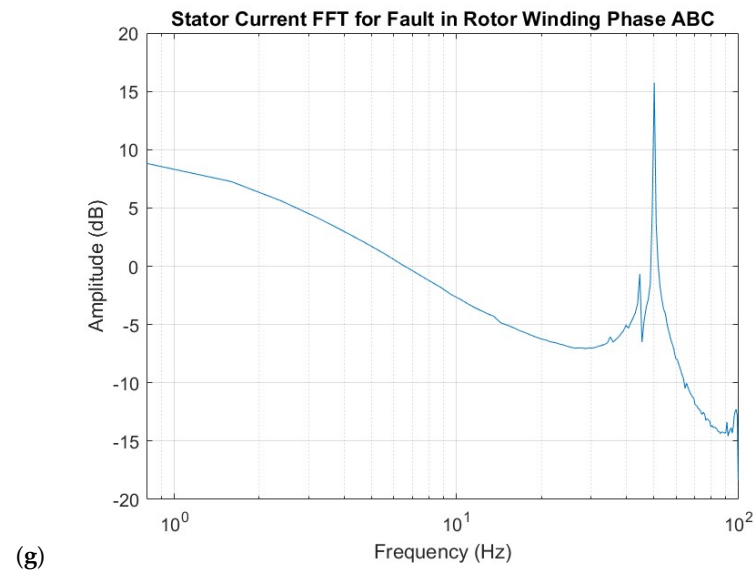


Figure 12. Stator current FFT for (a) H, (b) SWA, (c) SWAB, (d) SWABC, (e) RWA, (f) RWAB, (g) RWABC.

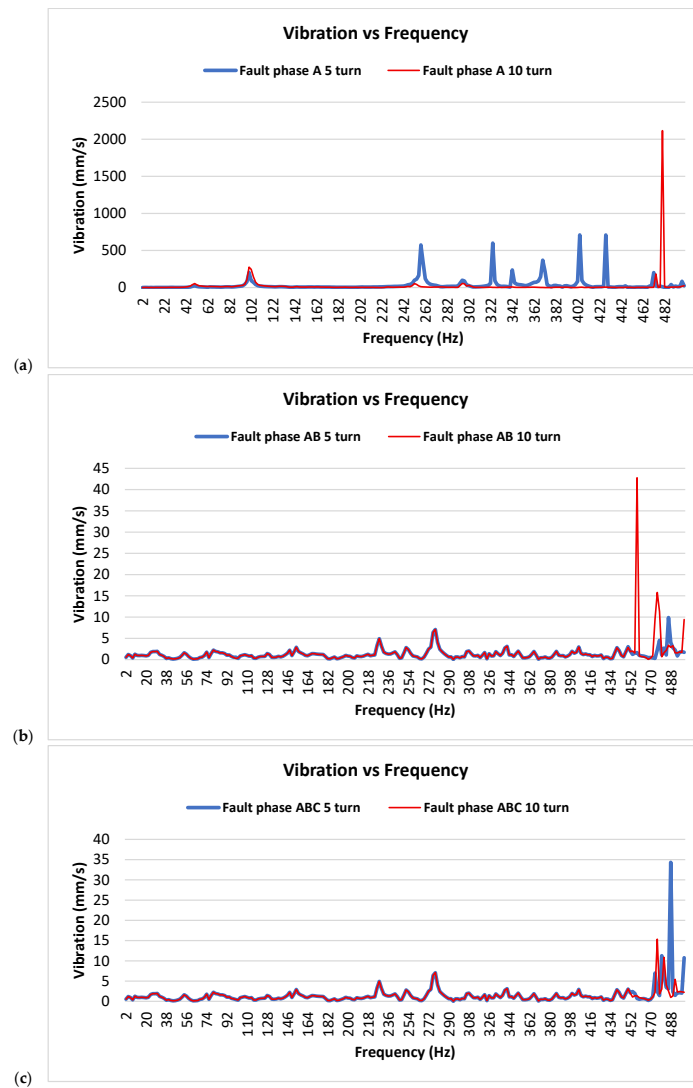


Figure 13. Vibration in mm/s vs. Frequency in Hz for 5 vs. 10 winding turns for (a) SWA (b) SWAB (c) SWABC.

4. Discussion

This section presents the capability of proposed study in terms of fault observability and CMS feasibility by sensing ITTFs in rotating electrical machines. It is a known problem that the detection of ITTFs is difficult at an early stage as it does not significantly influence the terminal currents. So, machine CMS is essential to diagnose the fault at preliminary steps and prevent catastrophic failure. Generally, SW fault diagnosis methods use magnetic flux, current and voltage or a combination of them. From a CMS point of view, SW ITTF can be detected by thermal protection, embedded resistance temperature detectors (RTDs), or temperature sensors as soon as a thermal hotspot is detected. Third-harmonic differential protection, if implemented, can also detect a current imbalance in the stator. The injection of a HF voltage presented in [41] can also be used to detect such faults early. The change in the leakage current before and after an ITTF as presented in [42] can also be used as a methodology to detect and diagnose ITTFs.

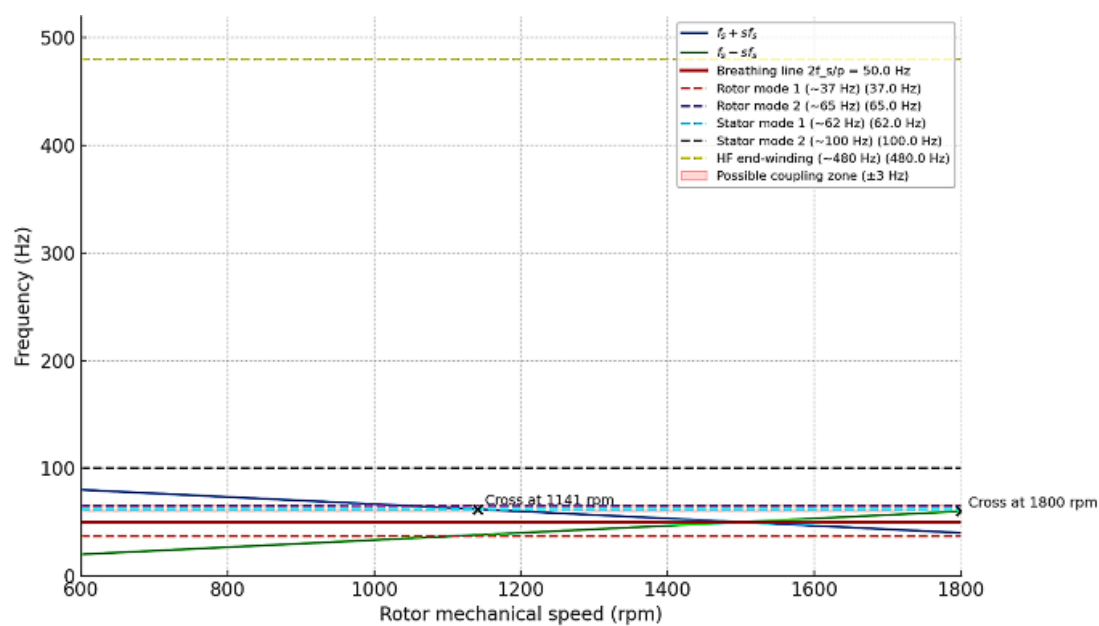
In [43], a method was proposed to predict stator and rotor ITTFs and even eccentricity fault indices by measuring the rotor direct and quadrature (d–q) axis currents and current controller error signals. However, early fault detection is difficult using impedance-based differential protection schemes, as the impedance per turn of a winding does not vary significantly. Stray flux measurement is another reliable alternative that uses a measurement device energized via a power plug that allows the stator core to be excited at HF (up to 400 Hz) and can lead to improved sensitivity in certain conditions. Injection at different frequencies allows faults to be detected deeper in the core and can be compared to ring flux measurement [44].

Rotor ITTF current on the other hand can propagate quickly, leading to excessive rotor current and tripping of the RSC and GSCs. It is also advisable to incorporate the following in existing WTU CMS frameworks: slip-ring inspection, infrared camera on end-windings, surge test if feasible, planned brush replacement/cleaning, inspection of end-winding supports, insulation spot check, integrated alarms for example based on calculations, and results around 1050–1140 rpm, as shown Figure 14a, for increased scrutiny of coinciding frequencies into Supervisory Control and Data Acquisition (SCADA)/CMS. Manufacturers must therefore install RTDs in SWs and monitor them with thermal relays according to ANSI 49, use harmonic signature-based protection on the rotor [45], etc., as shown in Figure 14c. Repetitive Surge Oscillograph (RSO) has been proposed in [46] for rotor faults. All CMS techniques stated above are feasible and some are standard industrial practices [47,48]. For example, study results in Figure 7 show the use of magnetic flux density as a method to detect surge in fault current. Executing flux monitoring such as fluxgate magnetometer, hall effect sensors, and the search coil (SC) magnetometer [31] is also a smart solution that works well in HF range.

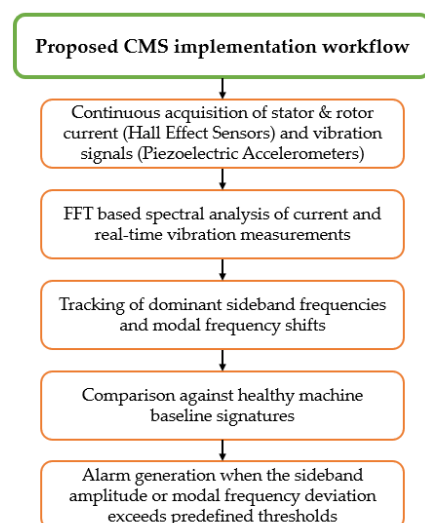
Contributions

Up on comparing MFs in Figure 11, sensors as discussed in [49] and manufactured by few industries such as MC monitoring, Switzerland has recently created a piezoelectric vibration sensor to measure frequency oscillations as low as 0.2 Hz [50]. Piezoelectric sensors must be installed on a stator frame near the drive end supporting the rotor shaft and non-drive end bearings supporting the slip-ring assembly. Current measurements should be obtained from existing stator and rotor current transformers (CTs). Rotor speed should be measured using an encoder or tachometer, and temperature should be monitored using embedded RTDs within the SWs. Uncertainty due to noise is excluded from this CMS workflow. Failure Modes and Effect Analysis (FMEA) tools to define reliability tests must be implemented by manufactures as part of machine CMS based on implementation workflow as proposed in Figure 14b. Likewise, DFIG protection co-ordination as seen in

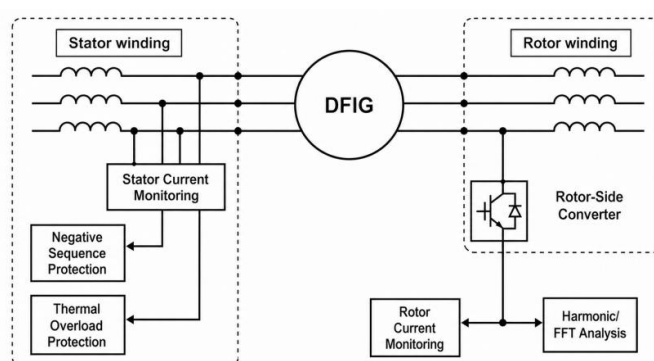
Figure 14c should be implemented to monitor SW and RW currents and implement FFTs to identify fault signatures compared to healthy stator current. Furthermore, vibration can be used to diagnose winding ITTFs as seen in Figure 13. Contribution from this research is summarized in Table 7.



(a)



(b)



(c)

Figure 14. (a) Frequency vs. rotor speed, (b) Proposed CMS implementation workflow, (c) Proposed DFIG protection scheme.

Table 7. Comparison of proposed conceptual alarm framework CMS for Stator and Rotor ITTFs.

CMS Aspect	Required Sensor/Method	Measured Signal	Fault Indicator	Threshold Values & Alarm Logic	Stator ITTF	Rotor ITTF
Vibration amplitude detection	Piezoelectric vibration sensor	Speed	Based on frequency sidebands	Warning: Vibration amplitude exceeds baseline by 20–30% or sideband amplitude exceeds predefined threshold.	Highly effective	Less effective directly
				Alarm: Exceeds 50% above baseline.		
				Trip: Exceeds ISO/IEC machine vibration limit or increase >10% per day.		

Table 7. Cont.

CMS Aspect	Required Sensor/Method	Measured Signal	Fault Indicator	Threshold Values & Alarm Logic	Stator ITTF	Rotor ITTF
Modal frequency shift detection	Tachometer or encoder for speed reference and FEA	Speed reference	Based on frequency sidebands & speed	Warning: Natural frequency shift > 2% from healthy baseline. Dominant excitation frequency within ± 2 Hz. Alarm: Shift > 5%. Trip/Inspection Required: Shift > 10% or resonance frequency approaches.	Smaller shifts	More effective because of large shifts
Current sideband detection	Current FFT	SW RW Current	Based on design SC current limit	Warning: Fault-related sideband amplitude exceeds healthy baseline by 6 dB. Alarm: Increase > 10 dB or exceeds design threshold. Trip: Sideband amplitude indicates estimated fault current exceeding allowable winding thermal limit.	Effective	Highly effective
Overall Proposed CMS viability	All of above	All of above	All of above	Warning: Any one indicator exceeds warning threshold. Alarm: Two independent indicators exceed alarm thresholds simultaneously (e.g., vibration + current sideband). Trip/Maintenance Required: Three indicators concur or one indicator reaches critical level.	Robust	Viable with adapted strategy

5. Conclusions

With the increasing dependency on renewable energy sources, it is vital to ensure that generators are dependable and robust. Worldwide instances of electric grids and power network tripping due to faults on wind farms and vice versa are witnessed, which have brought attention to reliability and protection of DFIGs. It is known from experience that early fault-detection techniques are of key importance to avoid failures. This paper compares the performance of a DFIG under baseline no-load operation at an ambient temperature of 22 °C for healthy and SW and RW ITTF conditions. EMT simulations were used to evaluate stator current behaviour, and modal analysis was performed to identify fault-induced vibration modes and structural responses.

- Assessments show stator and rotor winding ITTFs can lead to natural modes of vibration at different frequencies. These eventually perpetuate into vibrations.
- Modal analyses and FFT analysis have corroborated these results to comprehend possibility of resonance of faulty modes, for example, how ITTF increases sideband amplitudes causing excitation of 2nd mode of the rotor resonating with 1st mode of the stator as seen in Table 5. It must however be noted that rotor deformations are not as high as stator deformations owing to differences in build, design and damping assumptions.
- CMS implementation workflow and protection for no-load operating conditions with simplified thermal and material modelling based on SW and RW ITTFs based on stator vibration signatures has been proposed in this research. The study does not demonstrate converter dynamics, aerodynamic torque fluctuation, and grid disturbance. It is not experimentally validated and lacks mesh-independence study.

The present study however has a few limitations as the investigations were performed under no-load operating condition. Hence, the influence of full-load EM stress, converter switching dynamics, aerodynamic torque fluctuations, and grid disturbances on the vi-

bration characteristics were not considered. In addition, although mesh refinement was applied during FEA simulations, damping sensitivity analysis is proposed for future research. Also, lack of experimental validation, lack of mesh-independence study, simplified thermal/material modelling, impact of noise, and lack of real CMS field data has been considered for future research. CMS implications require confirmation under loaded/hot operating conditions in the future. Future work will also include a comparison of machines in fully loaded conditions with varying degrees of rotor excitation while ITTFs occur. Higher turns of RW ITTF cases will also be investigated further as only 5-turn RW ITTFs compared to SW ITTFs were simulated due to computational cost and expected similar trends.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing—original draft preparation, writing—review and editing, visualization, A.G.; Supervision, project administration, resources, T.R.C. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
CMS	Condition Monitoring System
DC	Direct Current
DFIG	Doubly Fed Induction Generator
EMT	Electromagnetic Transient
FEA	Finite Element Analysis
FFT	Fast Fourier Transform
GSC	Grid Side Converter
IEC	International Electrotechnical Commission
ITTF	Inter Turn Fault
MA	Modal Analysis
MF	Modal Frequency
MW	Mega Watt
POC	Point of Connection
RSC	Rotor Side Converter
RW	Rotor Winding
RWA	Rotor Winding ITTF in Phase A
RWAB	Rotor Winding ITTF in Phase AB
RWABC	Rotor Winding ITTF in Phase ABC
SW	Stator Winding
SWA	Stator Winding ITTF in Phase A
SWAB	Stator Winding ITTF in Phase AB
SWABC	Stator Winding ITTF in Phase ABC
VA	Vibration Analysis

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