Fault-Mitigation in Multi-Phase BLDC Machines - Literature Review

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***Abstract*—The move towards the more widespread use of electric motors in the automotive, rail, maritime and aeronautical industries has necessitated the need for robust, fault tolerant, control strategies within these safety critical applications. This paper investigates a range of faults, fault diagnosis strategies and fault mitigation strategies in brushless DC (BLDC) motors. The investigation has highlighted zero-sequence current injection as a high performance candidate for fault mitigation of multi-phase BLDC machines by utilising the harmonic content of the back EMF waveforms.**

I. INTRODUCTION

It is well known that electric motors can achieve higher efficiencies and better performance when compared to traditional internal combustion systems. In addition to this, we are seeing a large shift towards electric and hybrid vehicles in response to growing climate concerns. In 2019 the International Maritime Organization (IMO) estimated that marine transport is responsible for 2-3% of global greenhouse emissions [1], while in 2017 the transport sector contributed 24.5% of CO_2 emissions worldwide [2]. These factors make the introduction of electric machines in a range of transport applications a logical choice.

However, in order to achieve widespread adoption, especially in safety critical applications, fault tolerance is essential. Consequently there is a significant amount of importance placed on the fault tolerance of electric motors.

Brushless DC (BLDC) motors have advantageous qualities that make them preferable to other types of electric motors for use in the transport applications as we move towards the large scale integration of electric drives in these fields [3]–[7]. The characteristics of BLDC motors that make them desirable include, high torque density, high efficiency, a simple structure, relatively simple control, and low cost [8]–[12]. This paper investigates the types of faults in multi-phase BLDC (MP-BLDC) machines, as well as how they can be detected and compensated for to find areas for further research.

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A. Traditional BLDC motors

Traditional BLDC motors contain three phases and utilise rare earth magnets as a component of the rotor to produce magnetic fields for high efficiency and high power factor [3], [13]. BLDC motors achieve commutation electronically through use of power electronics that eliminate the maintenance issues associated with mechanical commutation.

The number of fault types, and the frequency of these fault types, are reduced in BLDC motors due to their winding configuration. They exhibit similar fault tolerance to switched-reluctance motors but with higher achievable torque density [14]. Each coil is wound around a single stator tooth which provides electrical, magnetic, and thermal isolation between phases. This means that a fault on one phase will be unlikely to induce undesirable voltages and currents on adjacent phases which would further deteriorate the performance of the machine.

B. Multi-Phase Brushless DC Machines

Multi-phase (i.e. > 3 phase) BLDC (MP-BLDC) machines contain the aforementioned characteristics of traditional BLDC motors in conjunction with higher fault tolerance due to the increased redundancy offered by increasing the number of phases. The distribution of power among the phases also makes them desirable in medium-to-large power applications as the power through each phase is reduced for a constant power rating. Consequently the rating of the power electronics decreases, and the fault compensation from each remaining phase is reduced in the event of a fault. Therefore, the amount that each phase needs to be over-rated for, in the event of a fault, decreases as the phase number increases. In addition to this, the impact of a fault on the performance of a motor decreases [15]. Reduced current through each phase lessens the need for parallelisation techniques for the switches, and allows a higher switching frequency to be applied [15]. This further reduces the size of magnetic components and reduces the filtering requirements leading to an increase in power density.

However, an increase in the number of phases also results in rising complexity and therefore an increase in the chance of a fault occurrence. Safety critical applications, such as those in the automotive, maritime, and aeronautical industries, have created a large focus on the fault tolerance of these machines. This includes looking at how BLDC machines will operate under different fault conditions; how the faults are detected before and after they have occurred; and, how the faults are compensated for when they arise.

Multi-phase BLDC motors also benefit from enhanced performance with a larger degree of freedom. This is exhibited in their reduction of current harmonics in the DC link; reduced amplitude and increased frequency of torque pulsations; and higher efficiency [4], [15], [16].

C. Paper Structure

The remainder of this paper is organised as follows: Section II looks at the typical faults that occur in BLDC and MP-BLDC machines; Section III categorises some of the fault diagnosis methods used and discusses some of the methods used; Section IV describes the model used to investigate fault-mitigation strategies; Section V discusses some of the fault mitigation techniques found in literature with particular emphasis places on stator winding faults; and Section VI draws conclusions and identifies areas for further research.

II. Types of Faults

Typical faults in BLDC motors occur as inverter faults, stator faults, rotor faults, sensor faults, and mechanical faults—such as bearing and gearbox failures.

Inverter faults include capacitor failures and short-circuit or open-circuit switches [3], [4], [11], [13], [17]. Capacitor failures can lead to large short-circuit currents and subsequent damage to adjacent components. Depending on the capacitor configuration, the isolation of faulted capacitors may result in the loss of operation of a phase, and a reduction in the DC link capacitance with a subsequent increase in the DC link voltage ripple.

A common stator fault is the short-circuit of windings which can result from the breakdown of insulation and is responsible for 30–40% of electric machine faults [18], [19]. This insulation breakdown may be due to voltage stresses, mechanical vibrations, thermal stresses, or the electrodynamic forces that result from the winding currents [13]. Stator winding short-circuit faults can range from just a few shorted turns, to all shorted turns. This results in high currents and therefore overheating of the affected phases, in conjunction with asymmetries within the machine. This overheating can increase the operating temperature of the motor and lead to an accelerated deterioration of the motor and total failure of the machine [20].

Open-circuit faults occur in stator windings due to burnt out fuses, wire breakage, or faulty wire contacts [20]. These faults create an imbalance, and a reduction in the torque producing capability of the motor. Paper [10] uses a mathematical model of a BLDC permanent magnet (PM) machine, which includes the non-linearity of the magnetic circuit and magnetic coupling between windings to observe the reduction of EM torque, and an increase in the torque ripple and speed ripple, in the presence of an open-winding fault.

Rotor faults include damaged rotors [13] which can reduce the magnetic field and cause irregularities in the flux distribution. Rotor eccentricities are caused by the displacement of the rotor centre from the stator bore centre. This results in distortions in the magnetic field and flux in the air-gap which affects the back electromotive force (EMF) waveforms. These faults can be caused by unbalanced loads and bent rotor shafts which arise during manufacturing, transport, and assembly. The two main types of rotor eccentricity faults are static, and dynamic faults. In a static rotor eccentricity fault, the rotor rotates over its own axis with a fixed air-gap distribution. In a dynamic rotor eccentricity fault, the rotor rotates over the stator axis with a variable air-gap distribution. These faults cause vibration, noise, and torque pulsations [21].

Hall sensors are used in BLDC motors to measure the rotor position so the correct commutation sequence can be applied. Sensors are often used in place of sensorless techniques for their superior performance in a wide-range of operating conditions. Hall sensor faults result in the output of the Hall sensor remaining in a constant state, either high or low, regardless of the presence of a magnetic field. These faults can arise from harsh environments, mechanical vibrations, faulty connections, or poor sensor quality [12]. Hall sensor faults can impact the performance of BLDC motors resulting in vibration and noise, additional damage to other drive components, reduced torque and potential stalling [8], [13].

The section has looked at the type of faults found in BLDC and MP-BLDC motors.Section III explores techniques that have been used to diagnose these faults.

III. Fault Diagnosis

Fault diagnosis is important to ensure that the faults can be corrected before system failure occurs. A system failure results in a loss of torque production and presents large safety concerns. It is therefore important to utilise fault diagnosis techniques that are fast, can predict faults before they occur, and allow sufficient time to implement a controlled shutdown for maintenance [13].

Fault diagnosis utilises model-based techniques and signal-based schemes to detect faults. These diagnosis techniques replace the need for hardware redundancy to compare healthy components against those being tested. In model-based techniques, the model receives the same inputs as the motor to compare outputs. Model-based techniques include analytical models, or knowledge-based models (such as neural networks) when the model is too complex or difficult to obtain. Signal-based schemes utilise time domain, frequency domain, or time-frequency domain signals to characterise faults [22].

A. Inverter Faults

Inverter fault diagnosis involves looking at short-circuit faults, open-circuit faults and capacitor breakdown. Signal-based techniques detect short-circuit faults and capacitor breakdown by looking at the magnitude of their respective currents. In phase modular configurations, each module has its own capacitor connected to the DC bus. High currents from capacitor breakdown cause a DC capacitor fuse to isolate and disable the module [17]. The single-switch open-fault diagnosis method is a model-based technique used in [11] to compare phase voltage measurements with their expected outputs. The state that the fault was found indicates the location of the fault.

A static fault diagnosis method for open-circuit and short-circuit faults is proposed in [4]. This method uses additional hardware implemented on the high and low side of a single phase, and the output of these sensors are used to signify a fault.

B. Stator Faults

Stator faults can be be diagnosed by monitoring a range of variables including the electromagnetic (EM) field, temperature, radiofrequency (RF) emission, vibration, currents, and voltages. These variables can then be analysed using analytical or knowledge-based models for fault detection.

Motor current signature analysis (MCSA) is a common tool used in fault detection that looks at the harmonic spectrum of the motor currents. Motor faults have characteristic fault frequencies which can be used to diagnose electrical and mechanical faults with MCSA . In [13], MCSA is applied with adaptive neuro-fuzzy interference system (ANFIS) to detect stator short-circuit faults. ANFIS utilises a knowledge-based model that has been applied to a wide range of control problems due to its flexibility.

ANFIS has also been used in [18] and [19] using the EM torque, and line-to-neutral voltages respectively. Both papers process these measurements using DFT and STFT and perform ANFIS twice to firstly determine the number of shorted turns, and then to indicate the faulty phase. In [18], dips in the EM torque wave correspond to short-circuit faults where the magnitude and switching state have a relationship to the number of shorted turns, and fault location respectively.

Turn-to-turn short-circuit faults are also diagnosed in [15] using a signal-based technique on a multi-phase machine. A diagnostic index which contains information on the harmonic content of two orthogonal reference frames yields a value of one under healthy conditions. When a fault occurs, the harmonic content of the voltages from each reference frame result in a change in the diagnostic index to a non-zero value to indicate the presence of a fault.

C. Rotor Faults

Rotor eccentricities cause changes in the air-gap which result in changes in the magnetomotive force (MMF) distribution. This can be observed as a change in inductance with rotor position. This property can be used to both diagnose and compensate for rotor eccentricity faults. In [21], the phase-to-phase inductance in a four phase BLDC is measured during each conducting interval by injecting high frequency currents and looking at the frequency content of the applied voltage and current.

D. Hall Sensor Faults

A fast fault diagnosis (FFD) method is proposed in [8] to diagnose Hall sensor faults. This method takes advantage of the repetitive sequence of Hall states under normal operation, and utilises a higher sampling rate than the commutation frequency. The FFD method measures the average commutation interval in steady state along with a maximum and minimum value. The FFD algorithm uses the expected Hall state in conjunction with the commutation time to diagnose a fault and then reconstruct the signal. This method has been shown to perform faster due to its faster sampling frequency and therefore shorter diagnosis time.

Paper [12] demonstrates that the frequency spectrum of motor current waveform contains information related to Hall sensor faults. The frequency spectrum before and during different Hall faults were compared and showed a distinct difference in the harmonic content of the current which can be employed in diagnosing Hall sensor faults.

This section has explored the techniques used to diagnose faults in BLDC and MP-BLDC motors. To be able to diagnose faults quickly, a comprehensive model is required. The following section will discuss the model used and implemented in simulation.

IV. Multi-phase BLDC Model

It is well known that (1) provides a simplistic model of a BLDC motor where $\mathbf{v}$ is the applied phase voltage vector, $\mathbf{i}$ is the phase current vector, $\mathbf{L}$ is the inductance matrix, $\mathbf{R}$ is the phase resistance vector, and $\mathbf{e}$ is the vector of back EMFs of each phase.

$$\mathbf{v} = \mathbf{L}\frac{d\mathbf{i}}{dt} + \mathbf{R}\mathbf{i} + \mathbf{e} \tag{1}$$

In this model the back EMF is dependent on the magnetic properties of the permanent magnet, the winding configuration and magnetic structure of the machine, in conjunction with the speed of the rotor. The back EMF was estimated in the implemented model using a trapezoidal waveform.

The electromagnetic torque produced by the motor is described by (2) where $\boldsymbol{\lambda}$ is the flux linkage of each phase.

$$\boldsymbol{\tau}_{em} = \boldsymbol{\lambda}^{\mathbf{T}}\mathbf{i} \tag{2}$$

The developed electromagnetic torque is dependent on the output torque which is in turn dependent on the machine parameters and the load torque ($\boldsymbol{\tau_L}$) as described by (3) where J is the moment of inertia, $\boldsymbol{\omega}$ is the angular speed of the motor, and B is the damping coefficient.

$$\boldsymbol{\tau}_{em} = J\frac{d\boldsymbol{\omega}}{dt} + B\boldsymbol{\omega} + \boldsymbol{\tau}_L \tag{3}$$

Equation (3) can be used to solve for speed ($\boldsymbol{\omega}$) and then integrated to determine rotor position.

This section has described the simplistic model used to analyse the performance of multi-phase BLDC motors under a range of operating conditions. The following section describes fault compensation techniques found in literature, and utilises the work from this section to validate the model used and the results obtained.

V. Fault Compensation

This section describes fault compensation techniques used for control of BLDC motors found in literature with emphasis placed on stator winding faults. The models and control strategies used in these papers have been replicated and then implemented on the BLDC motor model from Section IV.

A. Inverter Faults

A modular inverter design using a H-bridge configuration per phase provides an extra degree of electrical isolation between each phase and therefore reduces the impact that a fault will have on adjacent phases. Additionally, the H-bridge configuration means that the phase may continue to operate under fault conditions. The H-bridge configuration allows for 180° bipolar currents, and therefore the operation of an odd number of phases. A traditional three-phase BLDC motor with a three-phase two-level inverter only allows for the conduction of two phases at a time. The phase leg may continue to operate with unipolar switching in a H-bridge configuration in the presence of an open-circuit switch fault which acts to reduce the compensation required by the working phases, and also reduce the torque pulsations [14]. However, a trade-off of this design is the increased cost and volume associated with additional circuitry, and the added complexity and enhanced I/O requirements of microcontrollers, especially as the number of phases increases [3].

B. Rotor Faults

As mentioned in Section III, rotor eccentricity faults cause a change in the air-gap distribution which results in a change in inductance with rotor position. This property was used in [21] to compensate for these faults by incorporating the changing inductance values into the control algorithm. It was shown in that this method resulted in reduced torque pulsations.

C. Stator Faults

It was shown in [5] that compared to the standard pulses of current, controlled step-shaped current in BLDC motors increases the average power of the motor for the same RMS phase current at the expense of the torque-to-current ratio. Part II of this paper [23] demonstrated that this current control method has benefits in the event of an open-winding fault. The current step approach means that states that previously produced zero torque could produce a non-zero torque and therefore start up at no-load.

1) Algebraic approach: In [7] and [6], an algebraic approach was used to determine the currents to be supplied in a five-phase PM BLDC motor under healthy conditions, as well as fault conditions where a single or multiple open-phase fault was present. The choice of currents to be supplied during a fault were chosen such that Kirchoff's current law (KCL) was obeyed, and the RMS current of each phase was the same as the phase current under healthy conditions to prevent overheating. The model was implemented in *MATLAB* and results are shown in Fig. 1.

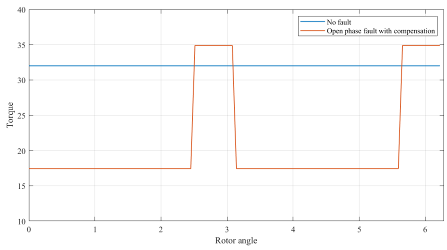

Fig. 1. Torque production before and after single open-phase fault in [7]

These results display a reduced output torque with significant torque pulsation in the event of a fault, even with current compensation implemented.

This same current compensation strategy, as shown in Fig. 2, was implemented in the model of a five-phase BLDC motor developed in Section IV. The blue waveforms display the current in each phase, and the red waveforms show the back EMF. This model also accounts for the torque ripple due to the switching devices used in the five-phase two-level inverter that would be used to control the same motor experimentally.

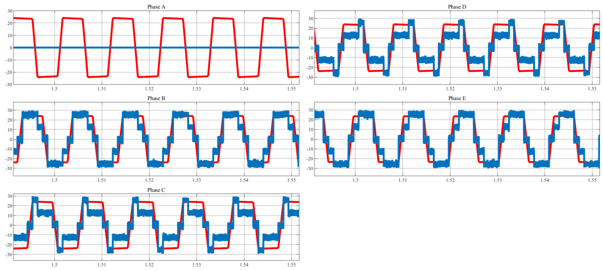

Fig. 2. Fault compensation current waveforms

This model also included the motor inertia and damping coefficient. Fig. 3 shows load torque and EM torque under open-phase fault conditions with compensation.

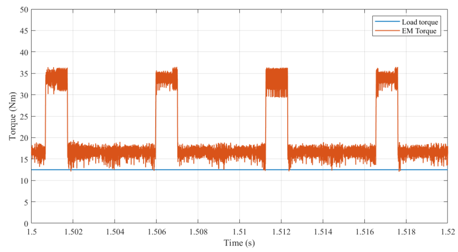

Fig. 3. Torque production after single open-phase fault with current correction

The torque ripple increased significantly as expected from Fig. 1 with additional torque ripple due to the switching electronics.

2) Quadratic programming: The proposed controller in [24] was designed to be applied to *n* phases and was verified in this paper using a three-phase model. The fault was detected using an observer and the co-variance of the error between the observer and the plant. The currents in healthy and fault conditions were calculated using quadratic programming optimisation. The aim of the controller was to minimise the power losses while meeting the torque requirements and not exceeding the phase current limits.

The fault tolerant controller was implemented by the authors of this paper in *MATLAB* using the model provided in [24] to verify the results. Fig. 4 shows the current waveforms when a single phase fault occurred at 0.3 s.

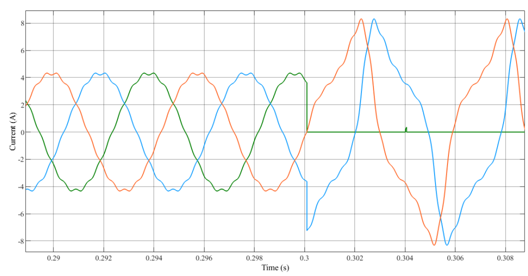

Fig. 4. Fault compensation current waveforms during fault occurrence

The fault tolerant controller was implemented experimentally on a three-phase BLDC motor in [24], and model limitations meant that there was a delay of approximately one second in diagnosing the fault which resulted in a large dip in the torque waveform. In this simulation, the plant and observer model were identical and resulted in a nearly instantaneous fault diagnosis. The torque waveform before and after the fault is shown in Fig. 5 and shows a small torque ripple after the fault has occurred at 0.3 s. The red waveform shows the EM torque, while the blue waveform shows the load torque.

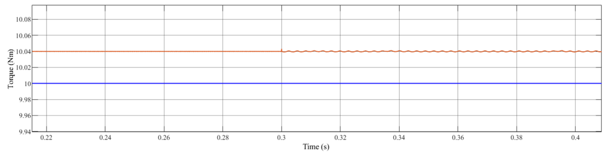

Fig. 5. Torque and speed waveforms during fault occurrence

The fault tolerant controller assumed the presence of a neutral line and did not investigate the currents present in the neutral wire in the event of a fault. When the fault occurred, a considerable amount of zero-sequence current was present as shown in Fig. 6.

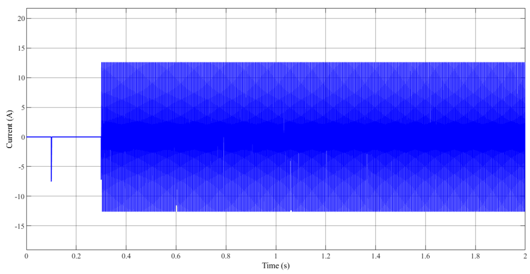

Fig. 6. Neutral line current before and after fault

The fault tolerant controller was then applied to the five phase model from Section IV. The back EMF waveform was modelled in the observer by performing a fast Fourier transform (FFT) and extracting the largest frequency components. The optimised current reference waveforms at the time of fault are shown in Fig. 7.

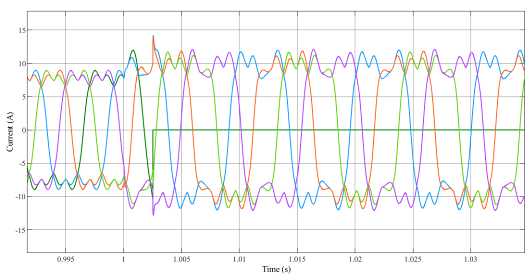

Fig. 7. Optimised current reference waveforms during fault occurrence

The EM torque and load torque waveform is shown in Fig. 8. This shows a torque pulse which occurred at the moment the fault occurred. The additional torque ripple is due to the switching components included in this model. This strategy also resulted in a significant amount of zero-sequence current during the fault conditions.

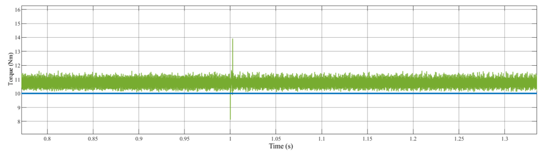

Fig. 8. Torque and speed waveforms during fault occurrence

The response time of the fault tolerant controller in [24] was dependent on the fault detection time. The controller had a fast response when a fault was detected with minimal resultant torque ripple.

3) Hamiltonian of optimal control: Some of the limitations in [24], such as the omission of the mutual inductances between phases, were addressed in [25]. The author utilised the Hamiltonian of optimal control theory to implement a fault tolerant controller which aimed to reduce copper losses and therefore increase the efficiency. This controller also considered the saturation of the terminal voltage when choosing the control input to prevent the associated torque ripple. Similar to [24], the model and controller used knowledge of the frequency content of the flux linkage as a function of the rotor angle in determining the input control voltage.

This multi-phase controller was simulated on a three-phase motor with a large damping coefficient. This simulation was repeated for verification. The torque and speed characteristic are shown in Fig. 9 under healthy conditions.

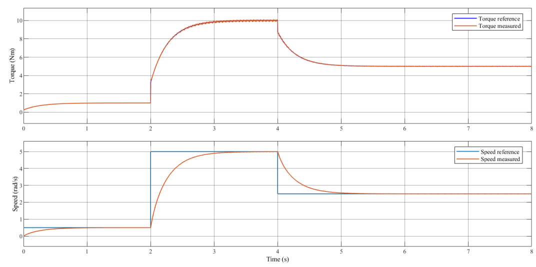

Fig. 9. Torque and speed waveforms in healthy conditions

This paper addressed open-phase faults and applied the controller to a three-phase motor with a single open-phase fault. The torque and speed waveforms for this controller are shown in Fig. 10. This figure shows an increase in the magnitude of the torque and consequential speed ripple compared to the healthy operation of the motor in Fig. 9.

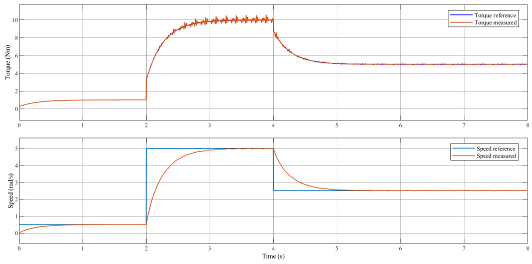

Fig. 10. Torque and speed waveforms with open phase fault

The zero-sequence current produced in a fault condition was not investigated in [25], however these simulations showed that zero-sequence currents were utilised in the event of a fault for the three-phase motor, as shown in Fig. 11.

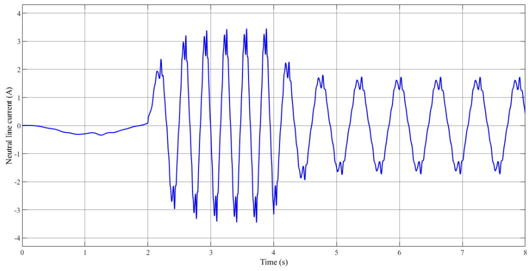

Fig. 11. Neutral line currents

This section has explored some of the fault mitigation techniques found in literature for a range of fault types. The following section will identify areas for further research within fault compensation.

VI. CONCLUSIONS

Each of the investigated fault mitigation strategies used for stator winding faults assumed a converter topology consisting of a single inverter leg to drive each phase. Therefore in healthy and fault conditions, in a wye connected machine, the currents must sum to zero in the absence of a neutral wire. It was shown that in fault conditions a neutral connection was assumed with intrinsic zero-sequence currents produced as a result which was not explored by the authors of the papers that were investigated. This review has highlighted the potential for zero-sequence currents to be utilised as a mitigation strategy in the event of a fault. This may be achieved by utilising a converter topology that allows these zero-sequence currents either through the use of an additional inverter leg, or a single converter to drive each phase.

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