Condition monitoring and severity estimation of rotor demagnetisation fault using magnetic flux measurement data

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Abstract
This article studies and investigates the magnetic characteristics of a surface mounted permanent magnet (SPM)-type brushless direct current (BLDC) motor when subjected to demagnetisation fault conditions. The proposed research subjugates the limitation of estimating the State of Health (SoH) of a BLDC motor drive when deployed in electric vehicle (EV) applications. Demagnetisation faults adversely affect the performance of a machine and indirectly the EV drive system, bringing significant transformation in the machine’s characteristics and quantities. The novel method of measuring the radial magnetic field ($B_r$) across the machine airgap assists in diagnosing and estimating the % severity of faults under the subjected fault conditions. A numerical co-simulation-based model of a BLDC motor is developed to investigate the performance of the machine under both healthy and fault conditions. The BLDC motor being studied is operated using a field programmable gate array (FPGA) based control drive adopting a hysteresis current control (HCC) technique. The experimental investigation of a complete BLDC motor test drive is carried out with an FPGA-based algorithm developed on the Xilinx ISE tool. The outcomes obtained are validated with the numerical results obtained through a finite element (FE) analysis. The proposed study uses a fluxgate sensor for experimental measurement of the flux density of a BLDC motor drive, which is vital for estimating the fault severity and scheduling the maintenance accordingly. The experimental investigations are found to be in validation with the proposed techniques in estimating the health of a BLDC motor-driven EV drive system.

1 | INTRODUCTION

Brushless permanent magnet (PM) or brushless DC (BLDC) motors are most widely used in industrial and commercial applications like electric vehicles (EVs). The BLDC motor has significant advantages with electromagnetic characteristics like high dynamic performance, high torque density and better efficiency [1, 2]. However, during continuous operation or unfavourable environmental conditions like physical and thermal stresses, BLDC motors are subjected to faults. Faults in brushless PM motors are generally on the rotor (PMs) and stator (windings) of the machine [3]. The comprehensive classification of faults related to PM motors is reported in [4, 5], while a detailed overview of demagnetisation faults and its identifying indices is illustrated in [6]. Among various available demagnetisation faults in the rotor, the fault due to a broken magnet is widely reported in the literature [7, 8]. The diagnosis of a broken PM demagnetisation fault has been done using different diagnostic methods, among which the advanced concept of measuring the leakage flux to detect a fault has been elaborated in [9]. A wireless sensor network (WSN) and the internet of things (IoT) [10] are also used for current unbalance estimation and consequently, the diagnosis of faults in the motor drive system. Pulse width modulation (PWM) and hysteresis control (HCC) [11, 12] are some of the most widely used FPGA-based control techniques adopted in industries for the condition monitoring of faults in a motor drive system.

The classification between rotor faults such as eccentricity and broken PMs and stator faults such as stator inter-turn faults (SITFs) is comprehended in [11, 12]. The fault...
diagnosis of induction motors having single and multiple faults using motor current signature analysis (MCISA) and vibration signal analysis based on machine learning algorithms is illustrated comprehensively in [13]. Similarly, in [14], a voltage-based approach is adopted for the diagnosis and classification of PMSM faults. In addition, another possibility of rotor demagnetisation faults, such as a gradual change in the magnetic properties of the rotor PMs which consequently alters the average magnetic flux in the machine, is illustrated in [15, 16]. Extensive analysis for diagnosing the bar breakage fault in the cage induction motor by carrying out the fast Fourier transform (FFT) of stator currents and reducing the spectral leakage of the same is elaborated in [17].

In [18], the finite element modelling (FEM) based approach is explained for inter-turn short-circuit faults in induction motors using electromagnetic signature analysis. While in [19, 20], the modelling of demagnetisation fault effects in the machine has been illustrated, and the corresponding change in the characteristic performance of the motor drive system is studied. In addition, the combined effect of faults is also investigated for classification; however, the % severity estimation of the fault is left unexplored in the literature.

Though the severity estimation of the fault in PMSM has been illustrated in [21, 22], it is limited to SITF only where the residual voltages have accounted for the % fault severity estimation. For a high-resistance connection (HRC) in a PMSM drive system, the estimation of fault severity is accomplished using the zero-sequence voltage component and stator current signature analysis as discussed in [23]. Similarly, an attention-based recurrent neural network approach with encoder-decoder architecture is proposed in [24], but it is again limited to diagnosing the stator inter-turn short-circuit faults only. Therefore, the % severity estimation of demagnetisation faults becomes vital and is necessitated while diagnosing the faults related to the rotor PMs of a BLDC motor drive.

This article therefore contributes significantly by investigating the possible demagnetisation fault effects as a consequence of other exiting faults like SITF (causing a high rise in stator currents and temperatures) which inflict a change in the magnetic property of rotor PMs. In addition, the percentage change in magnetic property of PMs is measured as a % to estimate its fault severity in terms of partial, irreversible and extreme cases of demagnetisation faults. Motor back-EMF (\(E_B\)) and radial airgap magnetic flux density (\(B_g\)) are some of the effective fault indices/indicators, which are used in this research to accomplish higher accuracy of diagnosing demagnetisation faults. These indicators when compared with the existing methods are found to be more accurate as they give an early alarm for fault conditions by indicating change in the motor back-EMF and airgap flux profile as and when the fault commences in the machine (demagnetisation in rotor PMs). Preventive measures can thus be taken with an early alarm indication of faults and the system can be protected from failure.

The proposed research therefore develops a numerical co-simulation-based model of a BLDC motor drive under both healthy and demagnetisation fault conditions. The laboratory setup of a closed-loop drive is built using a field programmable gate array (FPGA) adopting the hysteresis current control (HCC) technique. The Xilinx ISE tool is used for programming the control algorithm by incorporating the hardware description language (HDL) interface. The deployment of FPGA in the proposed research is due to its high processing speed and capability of performing complex computations, which are vital for investigating a machine’s characteristic performance under fault conditions. Moreover, the developed prototype can be deployed in EVs for estimating the state of health (SoH) of a motor drive system.

2 | DEVELOPMENT OF A BLDC MOTOR DRIVE SYSTEM IN CO-SIMULATED FE AND SIMPLORER TOOL

The finite element (FE)-based approach involves numerical modelling of a machine. The physical geometry of the machine is vital for building the FE model which requires physical dimensions as input machine parameters. The physical dimensions are considered in terms of stator geometry, which involves, the stator’s inner and outer diameter, its slot dimensions and slot shape, winding configurations like the stator’s winding arrangement (star or delta), winding material, number of conductors and turns per slot and the stator material. The rotor geometry involves the rotor’s inner and outer diameter, its permanent magnets (PMs); surface mounted PM (SPM) or inset PM (IPM) type rotor, width and height of the PM, type of PM and its \(B-H\) characteristic and the rotor material.

These physical dimensions and material properties of the machine and its components are given in Tables 1–3, which are used for modelling the actual BLDC motor being studied, in the FE tool. The motor drive circuit which comprises the three-phase voltage source inverter (VSI), FPGA controller, and measuring instruments is built on the Simpaler (similar to Matlab/SIMULINK) tool which is interfaced with the FE built BLDC motor to operate the machine in a closed-loop mode.

### Table 1: Electrical parameters of brushless PM synchronous motor

| Symbol | Parameters | Value    |
|--------|------------|----------|
| \(P_o\) | Output power | 850 W    |
| \(V\)  | Input voltage | 48 VDC   |
| \(P_w\) | Windage loss | 20 W     |
| \(N\)  | Motor rated speed | 2650 rpm |
| \(I\)  | Motor rated current | 21 A     |
| \(T_e\) | Motor rated torque | 3.06 N-m |
| \(\phi\) | No. of phases | 3        |
| \(\eta\) | Efficiency | 85%      |
The developed FE model of a BLDC motor under healthy operating conditions is shown through a meshed flux density model given in Figure 1. The rotor PMs are of a rare earth material, NdFeB, of grade N35SH and having a distinct BH characteristic or demagnetisation curve at different operating temperatures, given in Figure 2. The healthy operating temperature for N35SH grade PMs in a BLDC motor drive is below 80°C. However, for the demagnetisation fault conditions the temperature varies from 100°C to above 150°C depending upon the severity of fault.

### 2.2 Development of closed-loop drive system using Simplorer

For the operation of a BLDC motor under both healthy and demagnetisation fault conditions, an electric drive system is developed in a MATLAB-SIMULINK/Simplorer tool. The drive is further co-simulated in a closed-loop operation with the Maxwell 2D model of a BLDC motor. The motor drive is operated under 120-degree conduction as shown in Figure 3. The closed-loop drive comprises a multiplier block which is a wave shaping function $F(\theta_e)$ for a magnetic flux density $B_r$ or motor back EMF $E_R$. In this case, it is a quasi-square or trapezoidal wave shaping function because of the square wave switching characteristics of a BLDC motor given in (2), while the airgap magnetic flux density is given in (3).

$$F(\theta_e) = \begin{cases} 
1 & 0 \leq \theta_e < \frac{2\pi}{3} \\
1 - \frac{6}{\pi} \left(\theta_e - \frac{2\pi}{3}\right) & \frac{2\pi}{3} \leq \theta_e < \pi \\
-1 & \pi \leq \theta_e < \frac{5\pi}{3} \\
-1 + \frac{6}{\pi} \left(\theta_e - \frac{2\pi}{3}\right) & \frac{5\pi}{3} \leq \theta_e < 2\pi
\end{cases}$$

(2)

$$B_g = \frac{B_r}{1 + \frac{g}{b_m}}$$

(3)

where $F(\theta_e)$ is a magnetic flux density ($B_r$) reference function, $\theta_e$ is a rotor position or an electrical angle of the rotor, while $\omega_m$ is the mechanical speed of the machine under study. $B_r$ is the residual magnetic flux while $g$ is the length of an airgap and $b_m$ is the thickness of a magnet (PM). The speed controller comprising an adaptive PI controller has fast dynamic response to the change in speed during fault conditions. This is done in order to maintain the steady speed of the drive system for all operating
**FIGURE 1** The FE (numerically meshed) model of a BLDC motor with healthy magnetic flux density $B_g = 1.008-1$ T

**FIGURE 2** $B$-$H$ characteristics curve (demagnetisation curve) of a PM (NdFeB of Grade N35SH) at different operating temperatures

**FIGURE 3** A schematic of a closed-loop motor drive system modelled using Simplore-based electric drive and Maxwell built (FE) model of a BLDC motor
conditions. The steady state characteristics are studied to elucidate the performance of the machine drive under subjected conditions. However, the change in other electromagnetic quantities like stator phase currents ($I_s$), motor back-EMF ($E_B$) and radial airgap flux density ($B_g$) are monitored for the diagnosis of faults under transient and constant power mode operations.

### 2.3 FE-based measurement of electromagnetic characteristics (magnetic flux) of a BLDC motor drive

#### 2.3.1 Motor operations under healthy conditions

The co-simulation (of an FE built BLDC Motor and a Simplorer built electric drive) is performed on a developed BLDC motor drive operating under healthy conditions. The corresponding machine quantities in terms of stator phase currents, motor back-EMF ($E_B$) and radial magnetic flux signatures ($B_g$ and $\psi$) are analysed and given in Figure 4a–d. To achieve the stator phase currents of $I_s = 5$ A, the motor is operated at a mechanical speed of $\omega_m = 50$ rad/s, thereby generating the corresponding motor back-EMF of $E_B = 25$ V as shown in Figure 4a,b. The magnetic flux signatures’ analysis is performed on the machine where the flux quantities in terms of radial airgap magnetic flux density is found to be $B_g = 1$ T, while the flux linkage is measured to be $\psi = 0.022$ Wb, as given in Figure 4c–d, respectively.

However, under demagnetisation fault conditions the characteristic performance of the machine changes adversely, bringing significant change in the machine’s characteristic performance. The severity of the fault varies depending on the cause and intensity of faults. For instance, in the proposed study, the possible demagnetisation fault cases are modelled as

**FIGURE 4** (a) Stator phase currents of $I_s = 5$ A under healthy operating conditions. (b) BLDC motor back EMF, $E_B = 25$ V under healthy operating conditions. (c) For healthy motor operations, the radial airgap magnetic flux density is found to be $B_g = 1$ T. (d) For healthy motor operations, magnetic flux linkages $\psi = 0.022$ Wb
a consequence of high stator phase currents generated during the stator winding faults or SITF conditions, as will be discussed subsequently.

2.3.2 Partial demagnetisation (PD) fault conditions

When the stator currents in the machine are approximately at the rated values and the operating temperature of the PMs is above 100°C but below the Curie temperature, partial demagnetisation (PD) fault is initiated in the rotor PMs, as shown in Figure 5a. The subjected condition is practically encountered when the BLDC motor operates continuously for a long time in EVs. The machine quantities change adversely and a significant reduction in the motor back-EMF and magnetic flux signatures is observed, as given in Figure 5b–d. The distinct change encountered at the radial edges on the half cycles of the motor back-EMF, $E_B$ (Figure 5b) and radial airgap flux, $B_g$ (Figure 5c), validates the partial demagnetisation effects in the rotor PMs. Further loss in the magnetisation of the PMs validates the commencement of an irreversible

**FIGURE 5** (a) The high rise in motor phase currents (SITF conditions) commencing partial demagnetisation faults in the rotor PMs. (b) The distortion in the radial edges of the motor back-EMF’s half cycles identifying the partial demagnetisation fault. (c) Identification of the partial demagnetisation effect through the change encountered at the radial surface of the rotor PM flux density. (d) The reflection of the change in the radial surface of the flux linkages, which validates the partial demagnetisation effect in the PMs.
demagnetisation effect, with the average value of flux density reducing to 0.88 T. Similar reduction in magnetic flux linkages ($\psi$) going below 0.022 Wb is observed in Figure 5d.

2.3.3 | Irreversible demagnetisation fault (IDF) conditions

When the operating current is about 50 A (more than twice the rated machine current) and the temperature rises beyond the Curie temperature (150°C for NdFeB of grade N35SH, refer to Figure 2), the magnet attains irreversible demagnetisation fault conditions. The subjected fault conditions are encountered when the motors are operated at high speeds for a long time and undergo mechanical stresses and varying loads. In the proposed study, the IDF is emulated uniformly by 40% in two adjacent PMs of the machine. The FE (numerical) model of a BLDC motor under IDF conditions is given in Figure 6a. The IDF develops significant changes in machine performance characteristic in terms of proportionate

![Figure 6](image.png)

**Figure 6** (a) The FE (numerically meshed) model of a BLDC motor showing irreversible uniform demagnetisation faults (IDFs) in PMs. (b) Irreversible demagnetisation faults in rotor PMs where the $B_M$ reduces uniformly in two poles. (c) Irreversible uniform demagnetisation faults in PMs shown through reduction in motor back-EMF. Red: Phase A, Purple: Phase B, Blue: Phase C.
% change in the radial magnetic flux, which is found to be 0.63 T (approximate to 60%), shown in Figure 6b and a significant reduction in motor back-EMF given in Figure 6c, with a corresponding rise in stator phase currents. In addition, the detrimental reduction in $B_g$ and $E_B$ validates the demagnetisation fault conditions.

**FIGURE 7** (a) The FE (numerically meshed) model of a BLDC motor showing extreme demagnetisation faults in PMs. (b) Extreme demagnetisation fault conditions with a corresponding demagnetised pole’s $B_g = 0$. (c) Decrease in motor back-EMFs for an extreme demagnetisation fault. Orange: Phase A, Purple: Phase B, Green: Phase C. (d) Magnetic flux linkages’ profile showing the decrease in magnitude during extreme demagnetisation faults $\varphi = 0.016$ Wb.
2.3.4 | Extreme demagnetisation fault conditions

Extreme demagnetisation is encountered in the intense condition when the operating current is more than 80 A (more than thrice the rated values) and the temperature beyond the Curie temperature is maintained for longer durations. Extreme demagnetisation faults also commence in the machine due to the ageing of the PMs and manufacturing defects, which may separate the PM from the rotor frame. The PM may detach from the frame due to loads at the subjected environmental conditions and stress on the rotor shaft. In addition, the inverse magnetic fields on the rotor PMs lead to substantial loss in their magnetism, causing extreme demagnetisation conditions. In the proposed study, the extreme loss in two adjacent PMs is emulated by reducing the $H_C$ values uniformly to zero. A flux density model for an extremely demagnetised PM given in Figure 7a has $B_g = 0$ T for the corresponding demagnetised poles shown in Figure 7b. The motor back-EMF reduces to 4 V (tending to 0 V), while the magnetic flux linkages ($\phi$) reduce to $\psi = 0.016$ Wb, (72% of the healthy flux) given in Figure 7c,d, respectively.

3 | EXPERIMENTAL INVESTIGATIONS AND VALIDATION

3.1 | Instrumentation of experimental setup

An experimental test bed as shown in Figure 8a is set up to analyse the effects of a demagnetisation fault on the BLDC motor performance. The three BLDC motors of the rating and parameters as given in Tables 1–3 are used for carrying out the research investigation. The motor arrangement along with the fluxgate sensor is used for the measurement of the magnetic characteristics of the motor drive system.
The inner rotor BLDC motor having a surface mounted PM (SPM) shown in Figure 8b,c has magnetic flux sensors embedded on the stator periphery for measurement of magnetic flux. The motors being studied are viz. i. healthy motor (Motor-1), having $B_H = 1$T for the rotor PMs and faulty motor sets (Motor-2, 3, 4) having varied demagnetised rotor PMs.

For emulating the demagnetisation fault conditions, the magnetic coercivity is changed according to the % fault severity proposed in the simulation methods. For instance, the irreversible demagnetisation effects in the motor are emulated by heating the two respective PMs above 150°C (Curie) temperatures in a thermal chamber of a motor workshop. The heating is carried out until the magnetic flux, when measured across the complete surface of the PMs, is found to be approximately 55%-60% of the healthy $B_M$ when measured through flux metre. While assembling the motor, the two IDF affected PMs are then placed adjacent to each other in the rotor of a machine, which is referred to as ii. IDF-Motor-2, shown in Figure 8d. Similarly, for the extremely demagnetised fault conditions, the PMs undergoes high heating for longer durations until the magnetic coercivity reduces approximately to zero, $H_C = 0$ A/m when measured through the flux metre. The machine possessing the extremely demagnetised PMs is referred to as Motor-3, shown in Figure 8c. The demagnetisation of the N35SH PM follows a similar $BH$ characteristic, as given in Figure 2, which is the corresponding behaviour of a PM beyond the operating temperatures and its Curie point.

### 3.2 Drive control and measurement

The close-loop BLDC motor drive, shown in Figure 8a, has been developed using WAVECT Control and Flux Gate Sensor tools as given in Figure 9: (a) FPGA (Spartan 6) based real time control system and (b) FGMSD/125-C3T for flux measurements. The hysteresis current control (HCC) technique has been adopted for developing a control system in order to derive the

![Figure 10](image1)

**Figure 10** (a) Experimentally obtained motor phase current of $I_s = 7.5$ A under healthy conditions [$V_{ac} \sim 5$ V/div, $I_{ph} \sim 5$ A/div, $t = 10$ ms/div]. (b) Healthy motor phase currents obtained through co-simulation-based model

![Figure 11](image2)

**Figure 11** (a) Experimentally obtained $B_M$ for motor operating under healthy conditions [$V_{ac} \sim 10$ V/div, $t = 20$ ms/div] $B_H = 1.2 \sim 1$T [0.5 T/div]. (b) Numerically obtained $B_M$ of a motor under healthy conditions
switching pulses for a 120-degree conduction operation of a voltage source inverter (VSI). The WAVECT Controller is a compact, versatile real time control prototyping system which is used in synchronisation with the flux measurement sensors. In addition, the system comprises a dual core processor for control and communication, high-end FPGA for fast computing and IO, scalable embedded current and voltage sensors.

### 3.3 | Experimental findings

The BLDC motor drive under healthy conditions is operated at a rated mechanical speed. The stator phase currents and airgap magnetic flux density for Motor-1 is found to be 7.5 A and 1 T, respectively. The results are found to be similar when compared with the co-simulation-based model as given in Figures 10 and 11, respectively.

However, during the operation of Motor-2 having two rotor PMs under IDF conditions, the motor back-EMF and magnetic flux density changes. The change is initiated with a partial demagnetisation of the rotor PMs, which further commences the irreversible demagnetisation fault effect by causing a proportionate reduction in magnetic flux when measured through a flux gate sensor, as shown in Figure 12a(i). The back-EMF ($E_B$) for the demagnetised pole reduces to $E_B = 15$ V while the magnetic flux density is found to be $B_g = 0.6$ T, which is approximately 60% of the healthy flux density value. The results are similar when compared with the
TABLE 4  Harmonic components of motor back-EMF under healthy and demagnetisation fault conditions

| Harmonic frequency (k \( f_n \)) | 8 Hz (k = 1) | 16 Hz (k = 2) | 24 Hz (k = 3) | 32 Hz (k = 4) | 40 Hz (k = 5) | 48 Hz (k = 6) | 96 Hz (k = 12) | 160 Hz (k = 20) | 224 Hz (k = 28) |
|-------------------------------|--------------|--------------|--------------|-------------|-------------|-------------|--------------|---------------|---------------|
| Healthy                       | 1.40%        | 1.83%        | 3.13%        | 100%        | 2.89%       | 1.69%       | 30.68%       | 15.14%        | 7.52%         |
| Uniform demag.                | 6.7%         | 12.82%       | 18.36%       | 100%        | 10.52%      | 7.81%       | 30.51%       | 14.89%        | 7.30%         |
| Extreme demag.                | 28.86%       | 23.02%       | 21.49%       | 100%        | 14.92%      | 11.95%      | 30.45%       | 14.82%        | 7.27%         |

FIGURE 13  (a) Experimentally obtained hall sensor sequence of a healthy BLDC motor drive under operation [Y-axis: 1 div = 4 V, X-axis: 1 div = 4 ms]. (b) Experimentally obtained hall sensor sequence of a BLDC motor under demagnetisation fault conditions [Y-axis: 1 div = 4 V, X-axis: 1 div = 4 ms]

co-simulation-based outcomes given in Figures 5c, 6b, 12a(ii), estimating the % severity of the fault when the machine is under operation.

During the operation of Motor-3 possessing the two extremely demagnetised PMs, a detrimental reduction in motor flux density \( B_g \) (or \( E_B \)) to zero is observed. The decrease in the respective half cycles corresponds to the extremely demagnetised PMs, given in Figure 12b. The change in quantities is compared and validated with the co-simulation-based models which is found to be similar. The detrimental reduction of back-EMF to 2V or 0.08 T validates and estimate the % fault severity of a PM. In addition, harmonic analysis is performed using (4) on the motor back-EMF and the inferences are summarised in Table 4.

\[
 f_f = \left( \frac{n}{2} \right) f_s = n f_m \quad k \text{ or } n = 1, 2, 3 \ldots \quad (4)
\]

where \( f_f \) is the frequency of the \( kth \) or \( nth \) component in the spectrum, \( f_s \) is the rotational frequency, \( f_m \) is the electrical frequency while \( p \) is the number of poles. The odd harmonic of order \( n = 3 \) is third is found to be dominant, marking its significance in the identification and classification of demagnetisation faults. Additionally, the changes encountered in the hall sensor sequence are also contemplated as a reflection of demagnetisation faults in the machine drive. During healthy operation of the motor, the hall sequence displays a constant duty cycle, having a constant magnitude of 4V with a 120-degree displacement while during the demagnetisation of PMs, the duty cycle is not constant and varies, holding position 0 or 1 with a varying time period for a complete rotation of the motor, as shown in Figure 13a, b.

The changes in the hall sequence are due to the change in \( B_g \), which is a consequence of demagnetised PMs. The change in \( B_g \) directly affects the hall voltage \( (V_H) \) as illustrated through a relation of \( B_g \) with \( V_H \) given in (5).

\[
 V_H = -\frac{IB}{n d} = R_H \frac{IB}{d}
\]

where \( d \) = conductor length, \( n \) = carrier density, and \( R_H \) is a hall coefficient.

The demagnetisation fault in the machine is eventually diagnosed using the proposed methodologies and the severity of the fault is estimated based on the magnetic flux measurement data, as summarised in Figure 14. Moreover, the proposed methods of diagnosing the machine faults using radial magnetic flux signatures \( (B_g) \) and motor back-EMF \( (E_B) \) have been compared with the existing methods of fault diagnosis. Some of the fault indices have been compared with advantages and disadvantages as given in Table 5. It is found that the proposed method of diagnosing the demagnetisation faults using magnetic flux signatures is more accurate and effective in estimating the percentage fault severity in the machine.

4 | CONCLUSIONS

The proposed study investigates the demagnetisation fault severity in brushless PM motors using the magnetic flux measurement technique. Primarily, extensive study is carried out using a co-simulation-based numerical analysis, which is used as the reference for experimental validations. The laboratory instrumentation setup has been developed in view of the EV-based application, which continuously measures and monitors the flux data using the flux gate sensor/tool. The condition monitoring of a BLDC motor drive system deployed in industrial and commercial applications like EVs is
FIGURE 14  Estimation of demagnetisation fault severity in a BLDC motor drive under operation

| Fault diagnostic techniques | Mathematical formulation | Advantages (appropriate suitability) | Disadvantages |
|-----------------------------|--------------------------|--------------------------------------|---------------|
| Motor current signature     |                          |                                      |               |
| Analysis (MCSA)             |                          |                                      |               |
| [4, 5, 10, 12, 17, 19–22]   |                          |                                      |               |
|                             | \( v_i = R_i i_a + (L - M) \left( \frac{d i_a}{dt} \right) + \left( \frac{d i_y}{dt} \right) \) | Stator related faults viz. stator inter turn fault (STTF), intra turn fault, winding inter-phase faults. | Supply disturbances may lead to false indications. |
|                             |                          |                                      |               |
| Motor back-EMF signature     |                          |                                      |               |
| Analysis [4–7, 14–16, 19, 20]| \( \lambda_{PM} = \int f \, dt \) | Used as an additional information to diagnose and validate the existence of faults along with current and magnetic signatures. | Real time measurement is quite complex. |
|                             | \( \lambda_{PM} = \int f \, dt \) |                          |               |
|                             | \( e_s = \frac{d i_y}{dt} \) |                          |               |
|                             |                          |                          |               |
| Magnetic (flux)             |                          |                                      |               |
| characteristic Analysis     |                          |                                      |               |
| [6–9, 11, 12, 15–17]         | \( \lambda_{AB} = b_A \int f \, dt \) | Rotor permanent magnet (PM) related faults. | Armature reaction effect may lead to false indications. |
|                             | \( B_y = \frac{b_A}{\gamma_m} \) |                          |               |
|                             | \( B_y = \psi (B_{y, healthy}) \) |                          | Magnetic sensors cost very high and installation needs expertise. |
|                             |                          |                          |               |
| Vibration Analysis          |                          |                                      |               |
| [2, 4–6]                    | \( f_f = \left( \frac{1}{\phi} \right) f_s = f_m \) \( k, m = 1, 2, 3 \ldots \) | Mechanical faults viz. Bearing faults, eccentricity faults. | Aerodynamics friction and supply disturbances may lead to false indications. |
|                             |                          |                          |               |
|                             |                          |                          | Sensors cost in mid-range but needs permanent installation, |
accomplished through the developed mechanism. The proposed research applies to online diagnosis of rotor demagnetisation faults in a machine along with approximating the percentage (%) fault severity. In addition, the given techniques can be used to estimate the state of health (SoH) of the system by simply measuring and monitoring the magnetic flux data and alarm for severe fault conditions in advance. The magnetic flux data are found to be more reliable and informative for diagnosing the faults in their incipient stage, adding a novel contribution to the field of rotor fault diagnosis in PM synchronous motors deployed in industrial and commercial applications like EVs.

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