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AI-Driven Time-Efficient Fault Diagnosis of a BLDC Motor Drive for Electric Vehicle Applications

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Brushless Direct Current (BLDC) motors have become crucial in EV applications due to their great performance. The BLDC motor's torque-to-power density is increased because to the removal of rotor windings and the addition of Permanent Magnets (PMs). BLDC motors in electric vehicles are more susceptible to failure since they run continuously. PM-type BLDC motors are critical for electric vehicle (EV) applications, and this research demonstrates the time-efficient fault diagnostics of the motor in the event of a malfunction. Fault identification at an early stage is possible using the suggested diagnostic approach.

1. Introduction

Electrical equipment for mechanical processes may be designed with consideration for how electrical impulses are converted into energy. Movement may be generated by electrical impulses, for as by using a motor or actuator. Power is turned into mechanical energy through motors.

The most basic kind of motor is the brushed direct current (DC) motor. This kind of motor uses a fixed magnetic field to conduct electricity via a series of coils. Each coil's like and unlike poles are being pushed apart by the magnetic fields created by the current, which spins the coil assembly around its axis. Keep the current reversed so that the coil polarities continuously vary in order to keep the coils "chasing" the opposing fixed poles. The commutator, which is linked to fixed conductor brushes that make contact with each coil's winding, generates reversed current by spinning. There are two critical components of a DC motor: the commutator and brushes. Figure 1 depicts the brushed motor's fundamental functioning.

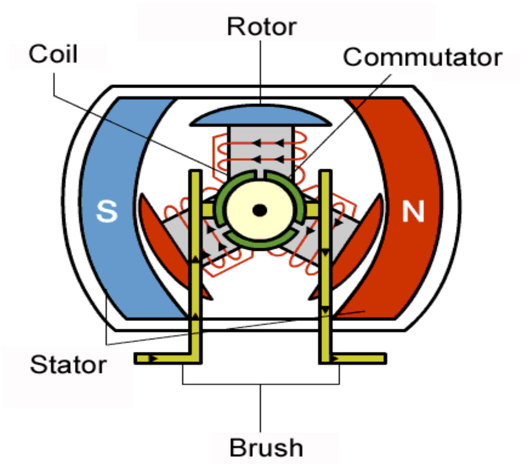

Figure 1: The Brushed DC Motor's operation

A series of fixed brushes powers the spinning commutator. Because of the commutator's ability to rotate in the opposite direction as the coils, the current flowing into them is reversed. The commutator must be connected to an external rotor in order to move.

Types of Motor Vehicles

When it comes to their power supply (AC or DC), as well as how they create spin, motors are vastly different (Figure 2). A short description of each type's characteristics and applications follows.

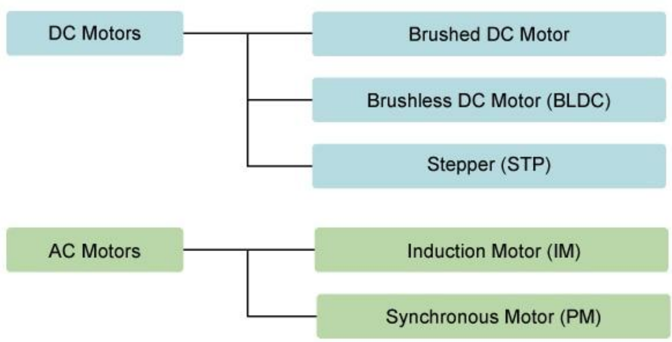

Figure 2: Various Forms of Power Sources

Brushless DC motors are often used to open and shut disc trays due of their straightforward design and easy operation. Motorized side windows are often retracted, expanded, and positioned in cars with the use of these systems. These motors are appropriate for a wide range of applications. Due to their continual interaction, brushes and commutators need to be replaced and maintained often.

Each pulse that is given to a stepper motor causes it to rotate over a specified range of angles, which is how stepper motors move. Since the number of received pulses can precisely govern the rotation of these motors, they are often used for positioning adjustments. Since an example, pulse count may be used to control paper flow in fax machines and printers, as these devices feed paper in predetermined stages that can be linked to pulse count. Pulse signals disturbed cause the motor to stop instantly.

Synchronous motors spin at the same rate as the supplied current. Microwave ovens with rotating trays may be used to cook food utilizing a reduction gear included into the motor unit. As with induction motors, the frequency of their rotation is not in sync with their motion. These motors have been used in electric fans and washing machines for a long time.

There are many different types of motors that may be found. Brushless DC motors are the focus of this presentation.

BLDC Motors Turn

As the name implies, these DC motors don't need brushes. Commutators are used in brush motors to move current from the brushes to the rotor coils. So how do the rotor coils of a brushless motor get current? It doesn't since the coils aren't attached to the rotor. A permanent magnet serves as the rotor, and the coils are attached to the stator. Commutator and brushes are omitted since the coils are stationary. As seen in image 3,

Brushless motors operate by altering the rotor's coil magnetic fields, while the stationary magnet magnetic fields remain constant. The speed of spin may be altered by varying the voltage provided to the coils. In a BLDC motor, rotation is accomplished by altering the magnetic fields provided by the stationary coils around the permanent magnet itself. This rotation may be controlled in two ways. First, you can alter how much or how little current flows into these coils.

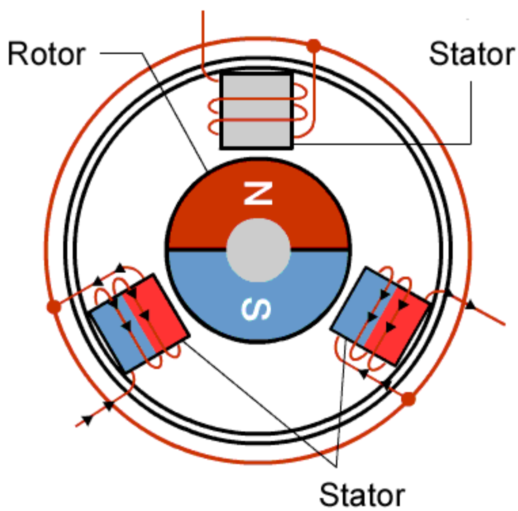

Figure 3: A motor with a BLDC (brushless DC) drive.

Since the rotor is a permanent magnet, no brushes or commutator are necessary. The fixed coils get controlled current from the outside.

Features of Brushless DC Motors

The stator of a BLDC motor with three coils will have a total of six wires running to it. Most often, three of these wires are connected within the motor, while the other three wires protrude from the motor outside shell (in contrast to the two wires extending from the brushed motor described earlier). Next week, we'll learn more about how these motors work, so don't worry about connecting the positive and negative terminals of the power cell. In the next sections, we'll examine the advantages of BLDC motors.

A key advantage in terms of efficiency is that these motors may run at their maximum rotational force continuously when needed (torque). Brushed motors, on the other hand, achieve their greatest torque only at certain points in the revolution. To provide the same amount of torque as a brushed motor, brushless motors need larger magnets. Even small BLDC motors may thus supply tremendous power.

Controllability, the second major advantage, is linked to the first. Feedback devices allow BLDC motors to be precisely controlled in terms of torque and rotation speed. Precision management to limit energy consumption and heat generation may improve the battery life of electric motors.

Due to the lack of brushes, BLDC motors have a longer lifespan and produce less noise. As a result of their continual movement, the brushes and commutators in brushed motors wear down and produce sparks. Electrical systems are notoriously noisy because of the sparks generated when brushes move over commutator gaps. The reason BLDC motors are chosen in noise-sensitive applications is because of this.

Applications for Brushless Dc Motors

BLDC motors have shown to be effective, controlled, and long-lasting. What are they used for? Because of their efficiency and durability, they are often used in equipment that runs continuously. With their high efficiency, they've been used for a long time in household appliances like washing machines, air conditioners, and more, but they're now being utilized in fans, where they've reduced power consumption dramatically.

Vacuum cleaners may also be powered by them. The motors' greater controllability was shown when the software controlling them was changed, resulting in a significant increase in rotational speed.

When it comes to spinning hard disc drives, BLDC motors are employed because of their long-term reliability and energy economy, which makes them ideal for this application.

Towards Future Wider Use

There will be more uses for BLDC motors in the future. It is envisaged that tiny, non-manufacturing-related robots, such as service robots, would play an increasingly important role in the future. If pulses can be used to precisely control the placement, stepper motors may be the most apparent solution. Since BLDC motors are superior at controlling the force, they should be used. A large and consistent current is required by a stepper motor to maintain the same position of a robot arm. BLDC motors can only be controlled by using external force, making them more efficient to control. BLDC motors, rather than the more common brushed dc motors, may soon be used in golf carts and mobility carts. Battery life may be extended even further by using BLDC motors, which are not only more efficient but also more precise in their control.

BLDC motors may also be useful for drones. Precision control is especially important for multirotor drones since it allows the drone's attitude to be precisely controlled by varying the rotational speed of each rotor.

The benefits of BLDC motors in terms of efficiency, accuracy, and long-term reliability have been shown in this lecture. However, in order to realize the potential of these motors, proper control is required. There will be a deeper examination of these motors when we meet again in a few of weeks.

2. Literature Survey

There is little amplitude in the motor torque that can be controlled by the FOPID torque controller. The FA technique is used to adjust the FOPID settings in this scenario. Efficacy of the proposed FOPID controller is tested in the Mat lab/Simulink environment by comparing it with a GA-based FOPID controller [1]

A functioning prototype is then constructed as the last stage in the process. As compared to the single-operating-conditions robust optimization results, the robust optimization technique increase the motor's durability. The torque ripple has been decreased by 38.4 percent, resulting in a reduction of 320% in cogging torque [2].

The fuzzy controller is capable of handling this issue since it is an intelligent controller. In this study, the BLDC motor is controlled by a fuzzy PI (FOFPI) controller. Optimizing controller settings using the Whale Optimization Algorithm (WOA). In order to ensure the system's resiliency, its performance was evaluated at a range of speeds [3].

The PWM is optimized using a specified look-up table as part of the proposed control approach for SHEPWM in order to reduce various losses at varied loads and motor speeds. MATLAB/Simulink simulation results are utilized to show the control mechanism's efficiency. It is necessary to test the control approach on an experimental 350W BLDCM drive system [4].

The proposed hybrid control technique has been compared to fuzzy-based and FOPID-based speed control systems. The recommended control method provides better and more accurate speed control across a wide range of speeds. The new controller's design reduces torque ripples under a variety of operating conditions [5].

In order to determine whether or not the proposed approach was suitable, the main goal was to test the power factor. MATLAB/Simulink is used to evaluate and compare the new visualization approaches [6].

It is possible to adjust the speed and torque variations of a BLDC motor using the ITSA algorithm. In this example, TSA search behavior is enhanced by using crossover and mutation operators. The strategy's output is experimented with using a speed and torque controller. Based on this, the most optimal gain values for controller performance are established [7].

Improved encoding the lower ripple voltage used in DC link switching improves output power quality while also reducing noise and vibration in the drive without affecting mechanical properties. It is cheaper to lower the number of switches in the system. Simulation of a Buck-Boost converter's performance under various operating factor scenarios is carried out [8].

The CCM and DCM operating modes and their influence on the Cuk converter's attributes are only two of the four unique modes of operation that are being investigated. Simulated findings from Mat lab/Simulink software are utilized to verify that the suggested system's performance study is accurate [9].

Active compensation and dynamic coupling must be tightly coupled in order for the LPF to function. In order to maintain a stable DC link voltage, this study suggests using a PR compensator. The suggested current ripple mitigation strategy for BLDC motor drive makes use of MSEPIC and DC link voltage selection circuits to test the PR compensator's performance. The PR compensator stabilizes the DC-link voltage while the DC-link voltage selection circuit generates a regulated DC voltage from the MSEPIC converter for efficient current ripple suppression throughout the commutation period. It has been shown via simulation and testing that the proposed compensating mechanism for the current ripple reduction approach of BLDC motor driving is effective. [10] Modeling and experimental results reveal that the PR compensator stabilized the DC-link voltage, easing the CCR.

A hybrid filter, a switched capacitor, and a spider web-based controller are all used in the torque ripple reduction circuit. The spider web controller regulates the voltages applied to the inverter switches and capacitors. For sensored and non-sensored activities, a Hall Effect sensor is employed, while a zero-passage point of counter emf is used for sensor less activities. Validating the effectiveness of a spider-based controller for a BLDC motor by simulating the motor in both sensored and sensor less modes [11]

The approach described above demonstrates that the proposed MPC-based controller is just as simple to implement as the PI controller while also offering superior control performance capabilities. With a BLDCM and a dSPACE1104 development board, the recommended BLDCM drive technique was tested and found to be successful. It has been shown via experimentation that the proposed driving mechanism is helpful.

PWM techniques used in low-speed BLDC drives fail to eliminate torque ripple at high speeds because the inverter input voltage is restricted. It is possible to lessen the high-speed commutation torque ripple by using a BLDC motor drive with a Cuk converter and mode switching selector circuit. To raise the voltage at the three-phase inverter input, an additional switch and diode are employed in the mode switching selection circuit to adjust the Cuk converter's output voltage during the commutation period. No need to switch between modulation approaches means the modulator may be designed more quickly. Modified bipolar PWM (H-PWM-L-PWM) is a method for switching inverters in both the conduction and commutation modes that utilizes a Cuk converter and a mode switching selection circuit. MATLAB/SIMULINK simulations and tests compare the effectiveness of the commutation torque ripple reduction approach [13].

Both loops of the MMFO-RNN protocol are responsible for achieving the most effective values. The MRPID controller encircles and controls ripple-free brushless direct current torque to achieve zero or minimal ripples [14]

3. Proposed Method

Permanent Magnet Type Synchronous Motors

There are three-phase windings on the stator of permanent magnet (PM)-type synchronous motors, as seen in Fig. 4. The form of the motor back-EMF is a major factor in categorising them. It is known as a Brushless Direct Current (BLDC) motor for a trapezoidal or square-wave back-EMF and a Permanent Magnet Synchronous Motor (PMSM) for a sinusoidal back-EMF [5]. Though the rotors of both motors contain PMs. The stator winding distribution and the form of the rotor magnets dictate the back-EMF shape. Figure 1 depicts the winding distribution for a PMSM and a BLDC motor, respectively Fig. 5. While the three phase terminals of a motor are typically supplied with quasi-square current, the PMSM needs sinusoidal phase currents to be excited. There are two types of rotor configurations: an inner rotor and an outer rotor, both of which use Surface Mounted PM (SPM) (IPM).

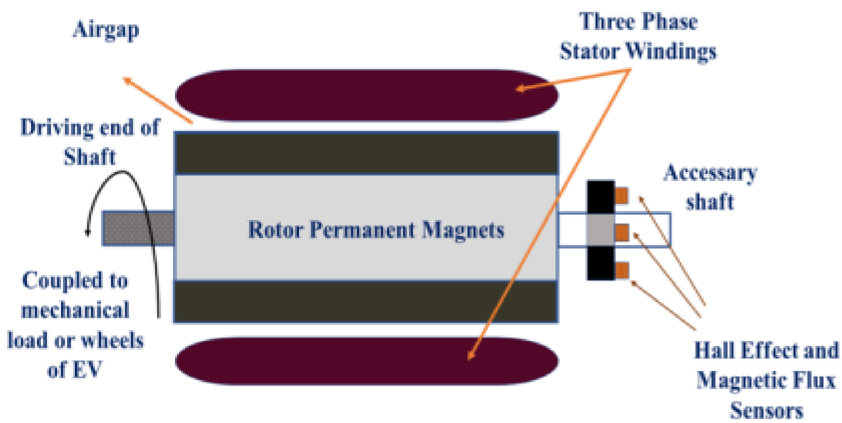

Figure.4. Schematic of a PM-type synchronous motor

Figure. 5. Physical geometry of PM-type synchronous motor available in laboratory

(includes both PMSM and BLDC motor)

High torque density and dynamic performance are just a few of the features that make brushless PM synchronous motors popular in a broad range of industrial settings [6]. The following is a list of popular uses:

- High torque density for automation and industrial use
- Servo uses of computer disc drives (compact)
- Airplanes (high torque to weight ratio)
- High flux weakening capabilities direct-driven wheel applications
- Uses in the Medical Field (noiseless)

FIG. 6 &7 illustrates how the two PM motors differ in their rotor airgap back-EMF. Both the form of the rotor PMs and the kind of stator windings are responsible for the trapezoidal and sinusoidal shape of the motor back-EMF.

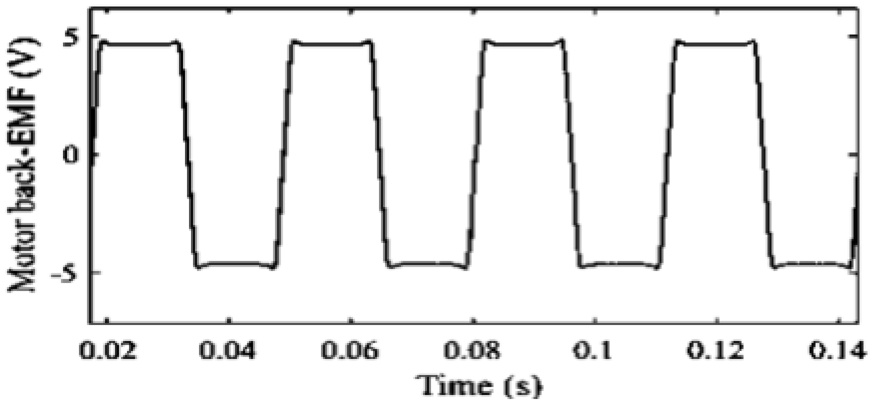

Figure. 6. Trapezoidal type back-EMF for a BLDC motor

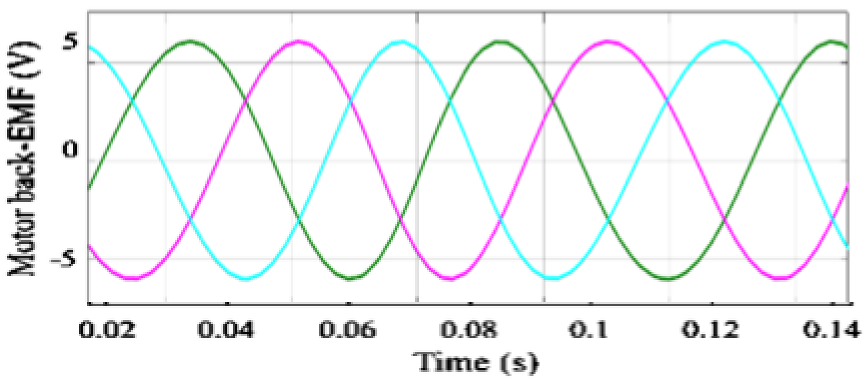

Figure. 7. Sinusoidal type back-EMF for a PMSM motor

Motor back-EMF may often be predicted using the formula (1)-. (3).

$$v_s = R_s i_s + (L - M)\left(\frac{di_a}{dt}\right) + \left(\frac{d\lambda_{PM,s}}{dt}\right) \quad (1)$$

vs is the phase voltage, i is the stator phase current, $\lambda PM,s$

is the flux linkage of a PM.

$Ls = L - M$, where, L is a self-inductance while M is the mutual

inductance between two windings.

ea, eb, ec are the back-EMFs due to PMs given by

$$e_a = \frac{K_e}{2}\omega_m F(\theta_e), \quad \text{for phase A} \quad (2)$$

$$e_a = \frac{d\varphi_a}{d_t} = \frac{d\theta_r}{d_t}\frac{d\varphi_a}{d\theta_r} = \omega_m \frac{d\varphi_a}{d\theta_r} \quad (3)$$

Back EMF constant Ke, rotor electrical angle e, mechanical speed ωm, φa stator flux linkage in phase-A winding, and F(θe) back EMF reference function are all included in this equation.

Bg is the airgap magnetic flux density obtained by dividing the motor back-EMF (4)

$$B_g = \frac{B_r}{1+\frac{g}{h_m}} \quad (4)$$

Where Br, g, and hm are airgap lengths and the magnet thicknesses, respectively, for PMs.

Under normal operating circumstances, the motor back-EMF and radial magnetic flux density must be employed as diagnostic signs for defect detection (EV applications).

Bldc Motor Drives Deployed For Electric Vehichle Applications

The machine power density is very important in HEVs, both pure electric and hybrid. The maximum operating speed (m) of an electrical machine determines its power density (PE) (5),

$$P_E = T_E * \omega_m \quad (5)$$

TE is the machine's rated torque, which dictates the machine's size and geometric complexity. This is why high-speed drive machines are used for constant power applications since they need less torque and hence a smaller construction with less complexity. Figure 3 illustrates the closed loop functioning of the PM based synchronous motor drives or BLDC motor drives.

The high torque/power density and dynamic speed capabilities of BLDC motor drives make them a high-performance speed drive appropriate for electric vehicle (EV) applications, as shown in Fig.4.

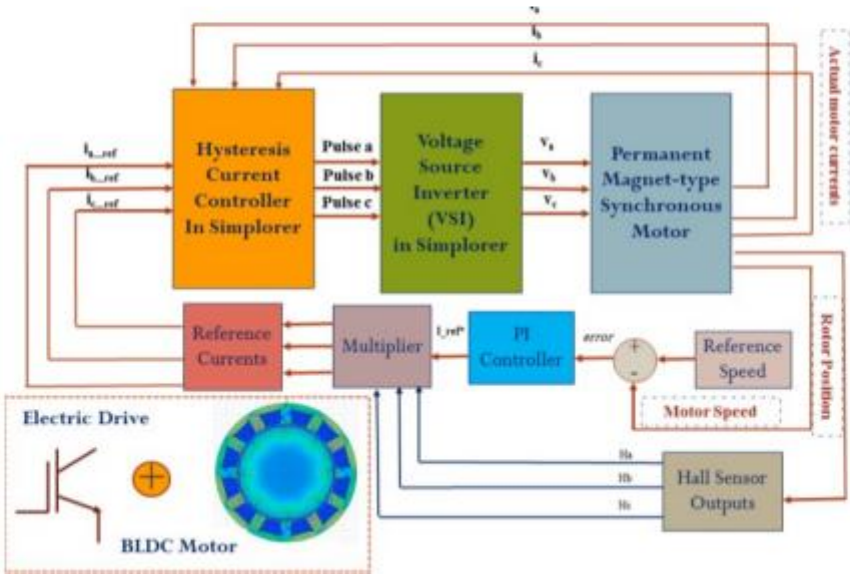

Figure. 8. Closed loop operation of a BLDC motor drive

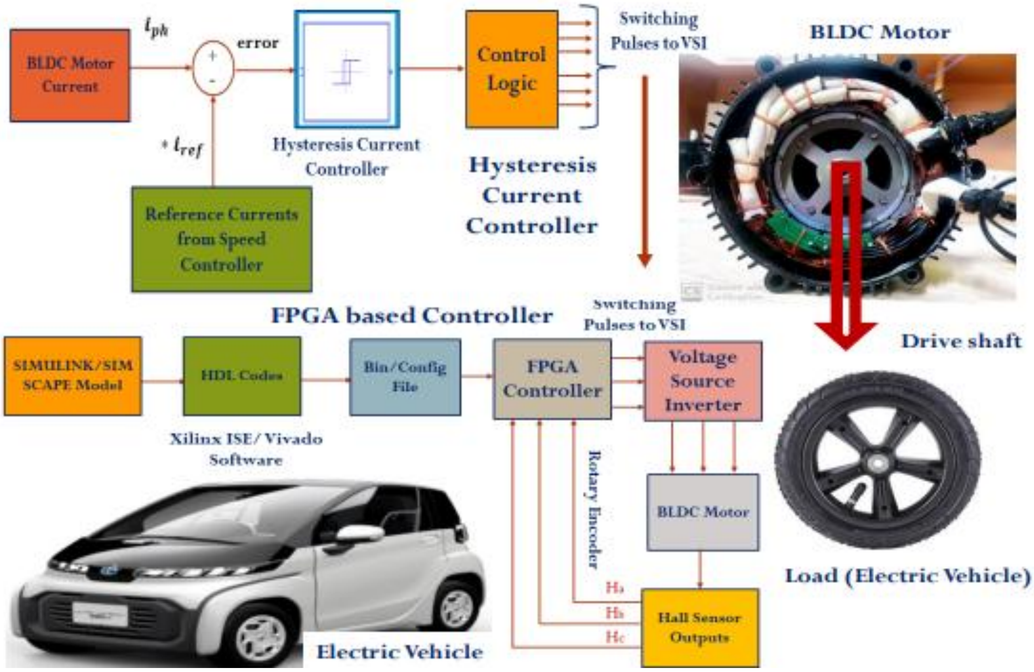

Figure. 9. BLDC motor driven Electric Vehicle drive

A BLDC motor's driving shaft is mechanically connected to a load, often an electric vehicle's wheel. As seen in Fig. 10, the EV's dynamic performance is consistent with the speed-torque curve.

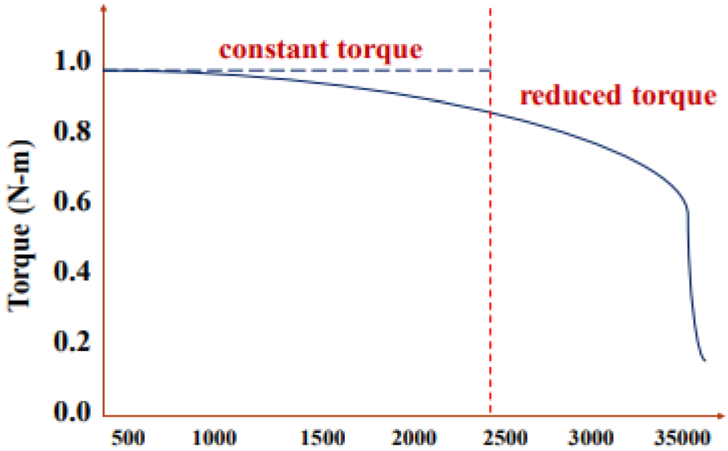

Figure. 10. Speed-torque characteristics curve of a BLDC motor

The BLDC motors, on the other hand, are susceptible to malfunctions while operating in poor circumstances. The EV's speed-torque characteristics are adversely affected when the motor's characteristics are compromised by a defect. The efficiency of the motor drive is greatly diminished as a result of this issue. Detection and diagnosis of motor problems must be made as soon as possible, in order to avoid additional damage. The quick diagnosis prevented the whole system from shutting down.

4. Results and Discussions

Characteristic Performance of BLDC Motor Driven Electric Vehicles Under Fault Conditions

As long as the working circumstances are healthy, the BLDC motor drive used in electric vehicle applications will operate as expected. The BLDC motor's operational mechanical speed is measured at a constant speed of m=50 rad/s in our research investigation. A torque of 2.1 N-m is produced by the electromagnetic motor. Figure 6 depicts the BLDC-powered EV's speed and torque characteristics under normal running circumstances. (a)-(b).

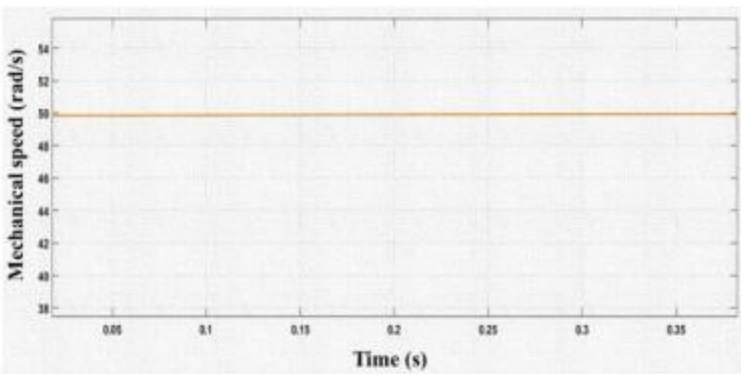

Figure. 11. Electromechanical speed of a BLDC motor drive under the loaded conditions.

The constant speed of ω_m=50 rad/s is maintained for the steady state operation of an EV

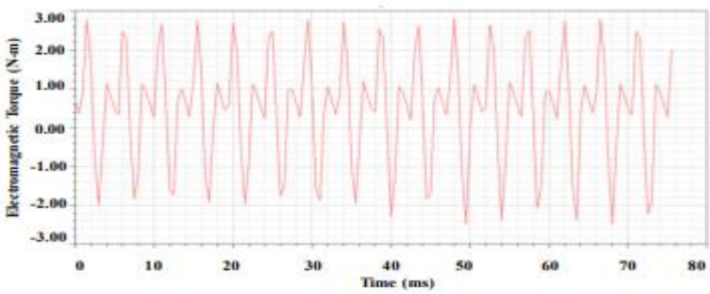

Figure. 12. Electromagnetic torque for the loaded conditions. The corresponding average torque inclusive of no-load torque (comprising of windage and frictional losses) is found to be TE= 2.1 N-m.

The motor back-EMF (EB) and radial magnetic flux density (Bg), which were previously determined in (2)-, were also considered important machine properties (4). While the EVs are running, these signatures may be continuously monitored to assess the machine's State of Health (SoH).

Figure 7 shows the motor back-EMF and flux density for the relevant operating conditions of the machine drive being investigated. As seen in fig 13 & 14.

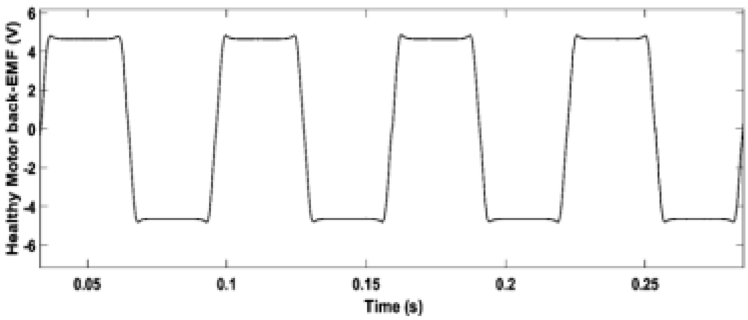

Figure. 13. Motor back-EMF under the loaded conditions where the applied speed generates EB= 4.5 V under the power constant operation of the drive.

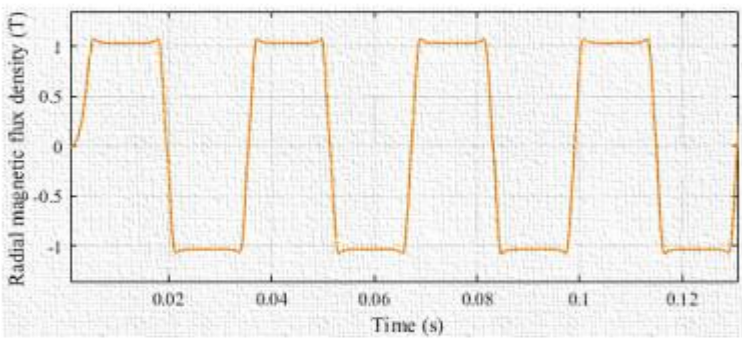

Figure. 14. Radial magnetic flux density of the rotor PMs under the loaded conditions. The

airgap Bg= 1T for the PM of grade NdFeB (N35SH)

However, the EV's performance suffers when the BLDC motor drive is exposed to fault circumstances while it is in use. As illustrated in Fig. 15 & 16, an early warning sign is a change in speed, which varies and becomes unstable. Fig. 15 depicts the resulting torque shift that occurs. Fig 16 and there is a decline in the performance curve. The motor's properties have changed in a way that does not necessarily indicate the origin of the problem.

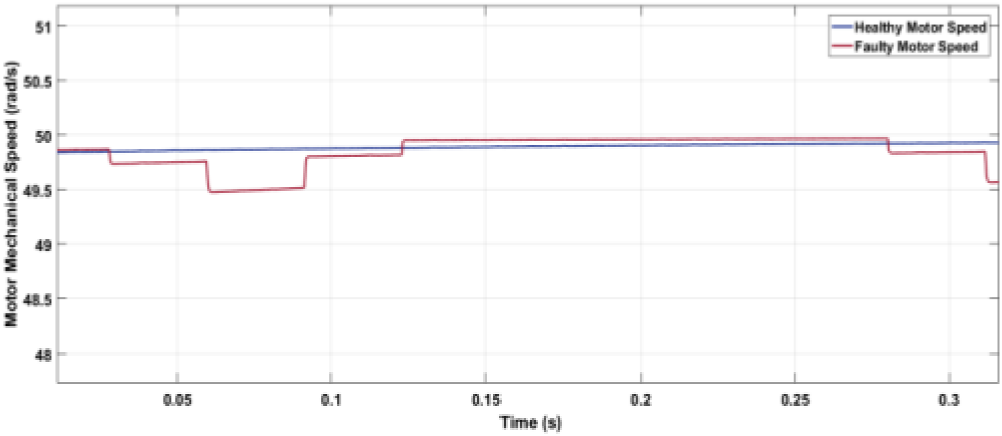

Figure. 15. Fluctuations in mechanical speed during fault conditions

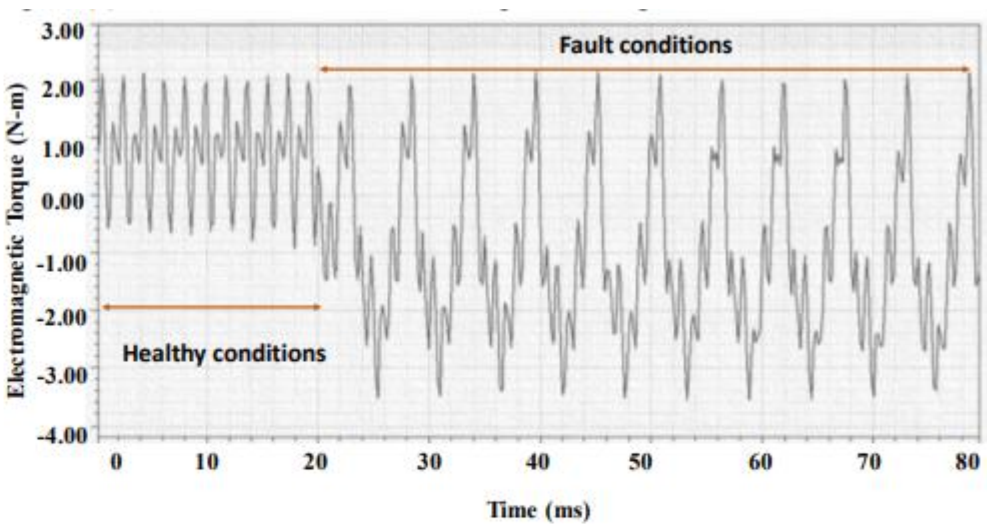

Figure. 16. High ripples in torque during fault conditions

Other monitoring characteristics, on the other hand, make it easy to pinpoint the source of the problem. There are several ways to determine what is wrong with a motor, such as analysing the back-EMF and/or radial magnetic flux signatures.

Figure 17 & 18 shows the motor back-EMF and magnetic flux for the relevant fault situations. The odd shift in EB and radial magnetic flux density for a broken rotor PM is further explored in [7] and shown to be the source of the observed EB and radial magnetic flux density variations. An electric vehicle's performance suffers when a BLDC motor malfunctions.

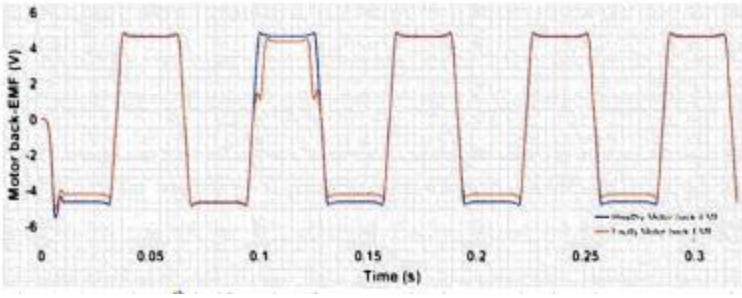

Figure. 17. The 4th half cycle of a motor back-EMF is showing an unusual change, confirming the fault in the PMs.

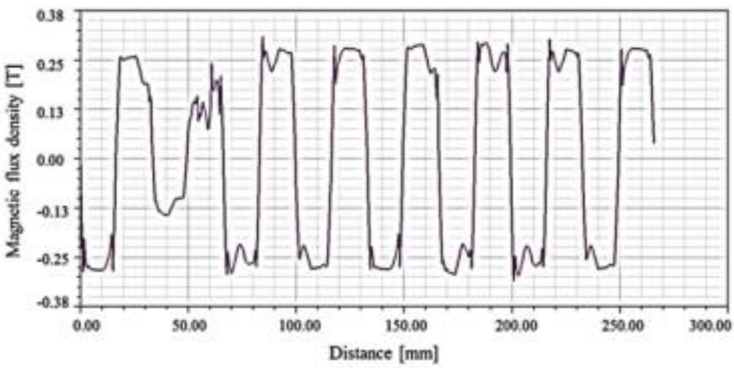

Figure. 18. Magnetic flux density of the 4th pole is distorted signifying and confirming the physical defects in the 4th PM of a machine.

As demonstrated in Fig. 19 & 20, the machine characteristics performance in terms of motor back-EMF and magnetic flux density is improved. Conclusion: The drop in rotor back-EMF, seen uniformly in Figure 19, demonstrates that the PMs have been demagnetized in an even manner [8]. Accordingly, as seen in Fig. 19 & 20, the shift in phase sequence and the corresponding non-uniform drop in motor back-EMF. When stator windings are shortened, [9] the machine is notified of Stator Inter-turn Fault (SITF) circumstances.

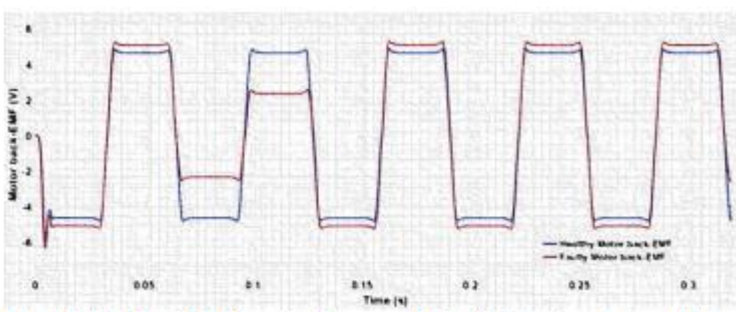

Figure.19. The 4th half cycle of a motor back-EMF is showing a uniform reduction in EB for

approximately 40%, signifying and confirming the uniform demagnetization fault in the rotor PMs of the machine.

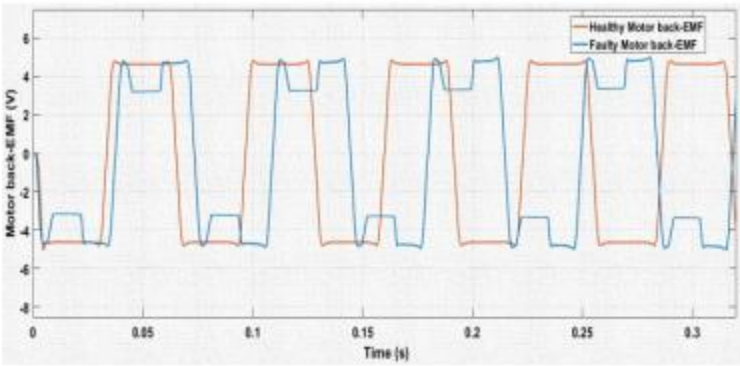

Figure. 20. Reduction and change in phase sequence in back-EMF of a machine under SITF conditions

Forewarning of fault situations is provided by continuous monitoring of electromagnetic signatures, and the relevant defects are detected in their infancy. To avoid the system from shutting down, a quick diagnosis is essential. Continuous (on the speedometer) monitoring of the motor back-EMF and radial magnetic flux signatures allows fast and accurate diagnosis of problem conditions in an EV. Additionally, preventative actions such as maintenance schedule may be successfully planned.

5. Conclusion

Permanent magnet (PM) synchronous motor drives for electric vehicle (EV) applications are critically important, and this study will go a long way toward explaining why. Industrial and commercial applications such as electric vehicles (EV) may benefit greatly from using Brushless Direct Current (BLDC) motors. By using the suggested fault diagnosis approach, it is possible to detect whether BLDC motor drives are vulnerable to malfunctions while they are still running. The online monitoring of motor back-EMF and radial magnetic flux density detects, identifies, and diagnoses the defect. The suggested technique is shown to be time-efficient since the problems are identified in their infancy.

Aside from that, the suggested method classifies the defects based on their typical behaviour, and preventative steps are done appropriately. Electric vehicle (EV) applications are determined to be appropriate, time-efficient, and viable using this technology.

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