Conditional Predictive Maintenance of Electric Vehicles from Electrical and Mechanical Faults

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Abstract

Maintenance of the core components of an electric vehicle is very crucial to ensure productivity, longevity, drive quality, and a safe environment. Predictive Maintenance is an approach that uses the operating & faulty condition data to predict future machine conditions and make decisions upon this prediction. The methodology used for predictive maintenance and condition monitoring can be based on machine learning and data analytics. The process of learning starts with the observation of data and using it in future instances for building the model. The primary aim is to allow the computer to learn without the involvement of the intervention of human assistance. A few machine learning methods are supervised learning, semi-supervised learning, and reinforcement learning. The main aim of the presented research is to use the available sensor data of the electric vehicle from various electronic control units and design a predictive model which classifies the various electrical and mechanical faults that occur in an electric vehicle and predicts the types for increasing the reliability of the whole electrical vehicular system. The workflow of the project is defined as fault modelling, generating healthy and fault data, processing the data using time synchronous averaging, identification of the system condition indicators and finally using these condition indicators, an SVM classification prediction model is designed from which the desired results and conclusion are inferred from the simulation studies.

Keywords: Predictive Maintenance, Electric Vehicles, Faults, Gear Faults, Electrical Faults, BLDC motor

INTRODUCTION

Electric vehicle (EV) was developed in the 1800 and was in high demand. Simultaneously the development of gasoline powered cars with cheap availability of fuel, and cheaper overall cost as compared to an electric vehicle, EV costed $1,750 while a gasoline car sold for $650 and due to other developments in IC engine vehicles, the electric car disappeared by 1930. In the next 30-40 years, gas shortage sparked interest in the electric vehicle. The electric vehicle industry has been a focal point from last few decades. With the increase in gasoline prices and environmental concerns among the mass, there is a rapid growth in the production and demand of electric vehicles in the coming future. Simple structures and control strategies have led to better vehicle management. It does not use any stored energy or cause any harmful emission and is capable of frequent start-stop drives, also preferable for motorsports. But EV's are still under the weak circumstances of low driving range, inability to charge rapidly, lack of enough charging stations, and expensive replacement costs. From survey [1] it is concluded that mostly repair costs and the range of EV's are the matter of concern.

Repair costs include battery replacement and motor part replacement costs. Even small damage can result in a costly breakdown. To solve this issue early fault diagnosis and predictive maintenance can be done which allows for determining the condition of in-service equipment.

Fault diagnosis for conventional gasoline vehicles has been investigated and analyzed [8-10] but not for electric and hybrid electric vehicles. However, currently, there is much research going on for the electrical system. Electrified vehicles have several crucial components such as motors, batteries, power electronics, thermal units, and gearboxes. These components can face problems and diagnosing in the early stage and giving a solution for the issue is important and beneficial. Electric motors have played a key role in automotive technology and the increasing trend of electric vehicles shows in the increasing deployment of electromechanical devices. Since motors are the driving force and determine the performance of vehicles our primary focus will be motors. Due to several factors cost, efficiency, response, and control Brushless DC motors (BLDC) are widely used in industrial applications including EV's.

In [6] modelling of DC brushless motor by considering the commutation phenomenon. They have also analyzed and studied the patterns of stator back electromotive force (EMF) for the prediction of dynamic characteristics of BLDC motor drives. Control methods for BLDC are constantly developed. A PID control in analog and hybrid control to enhance their responses is explained by averaging out the operating states using rapid prototyping and dSPACE [7].

Common fault diagnostic techniques are rule-based and decision tree-type, but these have some limitations. A rule-based system faces issues in acquiring knowledge and making a reliable system and a decision tree can be large for a complex system and is system-dependent. In [2] a black box-type model with polynomial algebraic expressions with a BLDC machine is described. In that normal and faulty operating conditions are compared and analyzed if any mismatch with the normal condition is detected then there is a declaration. The limitation here is this type of process losses focus of the system and does not give information on the location of the fault. In [3] motor fault diagnosis is done by vibration analysis, proposing a method using modal analysis. The issue here is that the user himself cannot do the modal test and get the vibration library. there is a need for high reliability with an effective maintenance system for the machine. Past studies have demonstrated that techniques for predictive maintenance approaches can ensure high performance and reliability [11-13].

For the faulty parameter analysis, a model is simulated in MATLAB. Using the data collected from the simulation what type of fault and when it can occur can be analyzed. This will be implemented using Machine Learning techniques. Classification and Regression algorithms are used in this paper for the predictive maintenance of the motor. EV subsystem simulation model, different EV failures, causes and diagnostic methods, with more importance to Machine learning-based predictive model for motor fault diagnosis presented in this paper.

FAULTS IN ELECTRIC VEHICLE SUBYSTEM

EVs have been studied for a few decades concerning the core components which are battery, motor, and power electronics. There are two types, distributed driving electric vehicles and traditional ones. In distributed driving, there are four or more motors which are separately regulated. These types are advantageous but are more prone to faults. Firstly, batteries were introduced for fault diagnosis, as these are important for the propulsion of the vehicle. Any damage to the battery can influence the overall efficiency of the system. In the U.S. it is stated every HEV, or EV must be equipped with a maintenance indicator from the manufacturer [4] for the user end. The major faults in batteries are summarized as Overcharge or Over-discharge, Short Circuits, Overheating, and Inaccurate estimations.

Second, comes the motor, PMSM and BLDC motors have high efficiency and desirable than other machine types. However, like all machines, they have the possibility of failing. Moreover, the presence of rotating permanent magnets, and damage to the machine due to stator winding faults or disconnected from the line. The faults are categorized based on the root cause of the fault. There are Electrical and Mechanical faults. in electrical faults, an unbalanced inverter output to the motor can result in an unbalanced current and magnetic field. There are several fault diagnostic methods such as motor current signature analysis, oil & gas analysis, vibration analysis, temperature measurement [4].
Major faults are summarized as below:

- Short circuit or open circuit of stator windings,
- Rotor eccentricity
- Broken rotor bar
- Bearings faults
- Local gear and distributed faults
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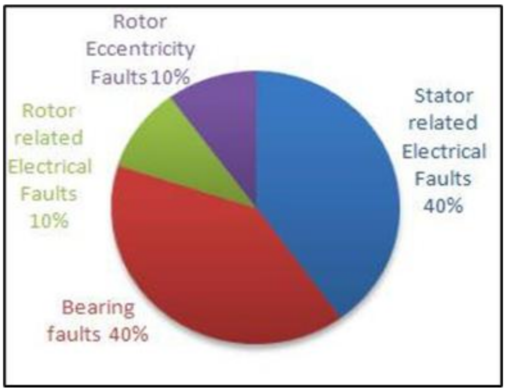

Figure 1: Motor faults occurrences

Thirdly, power electronics include all the power converters like inverters and controller circuits. It plays a crucial role in power exchange in the hybrid & electric vehicles. Currently, there is various research on solid-state devices used in converters [5]. The major faults in the inverter circuit are as follows:

- Open and short circuit
- Reversed diodes

In this paper mainly motor and power electronic faults are analyzed, and relevant data is collected for further modelling. There is accomplished research on fault diagnosis methods, but the main issue is they are not condition-based but focused on time-based monitoring. Condition-based monitoring and early fault detection of motor and power electronics will improve the vehicular system.

EV SYSTEM SIMULATION MODEL

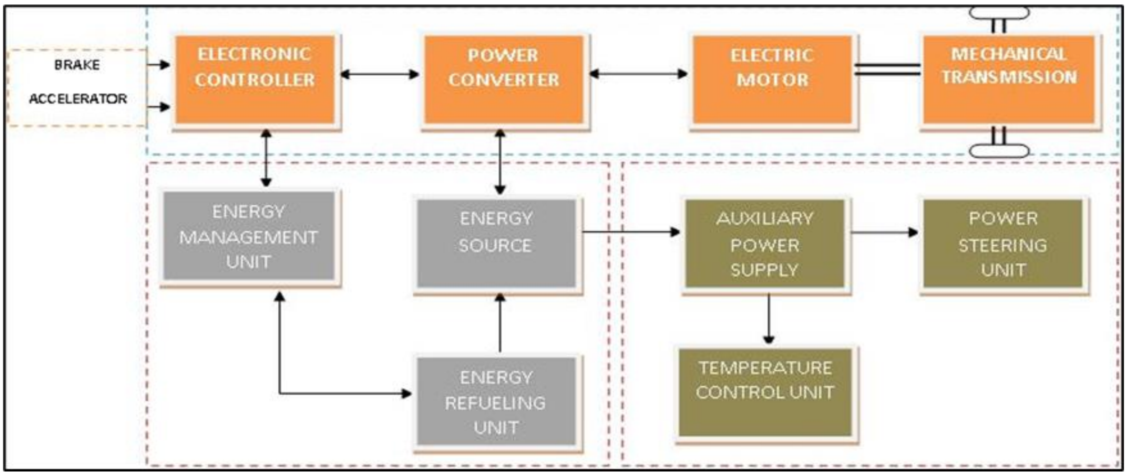

Figure 2: Block diagram of EV

EV system mainly consists of three subsystems i.e., electric propulsion subsystem, energy source subsystem, and auxiliary subsystem. Each of these systems interacts with each other to make the EV work and there are various technologies to operate the subsystems. Propulsion subsystems consist of an electric controller circuit, an electronic power converter circuit, motor, and transmission system whereas in a conventional car IC engine and motor are responsible for propulsion. The energy source system includes the battery pack and battery management unit. Few parts must work extensively with others whereas some must interact less. Various motor technologies for EV application are as follows:

- Permanent magnet synchronous motor
- Brushless DC motor
- Induction motor
- Switched reluctance motor
- DC brushed motor

Battery technologies used for EV application are Lithium-Ion, Nickel metal hydride, lithium polymers batteries and other common batteries can be used for EV. But the mostly used and efficient motor used is BLDC motor and 53% of electric vehicle industry uses Lithium-Ion battery packs for the energy source.

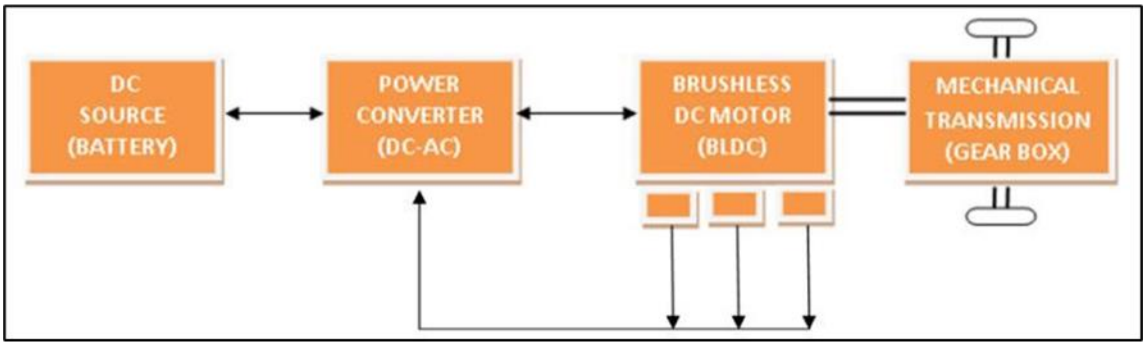

Figure 3: Block diagram of motor drive

1. **DC Source**: Batteries cover 40% of the EV cost. These are used to power the propulsion of vehicle. Lithium ion is majorly used batteries for EV's. There are batteries which claims that it can charge the EV in just 15 minutes which is affordable for the end users. Here the source voltage of 300V is provided by the battery pack to motor.

2. **Power Converter**: Inverter which converts the DC source to AC source. Here the six-step inverter's output is fed to the stator windings of the three-phase motor. The inverter gate signals are produced by decoding the hall effect signals from the motor.

3. **BLDC Motor**: For an EV application suitable motor will have high power to weight ratio and in case of brushless DC motor, ratio is high compared to other motors. Due to high efficiency, simpler power electronics control, faster response it is widely used in various industries. Several hall effect sensors are attached to the motor.

4. **Sensors**: In an electric vehicle there are hundreds of sensors present for the feedback control. Here for current, voltage, torque and speed sensing hall effect sensors are used. The signal from the sensors is fed back to inverter gates to control the switching. Sensors for motor output parameters are placed on the motor structure for efficiency.

5. **Gearbox**: One of the main differences in an electric vehicle and IC engine cars is the drivetrain. In an IC engine there is multi speed transmission which accommodates several gears whereas is EV selecting a single gear ratio, it has single speed transmission because of the motor speed characteristics. Here the gearbox consists of 13 tooth pinion and 35 tooth gear and accelerometers attached to gearbox operate at sample rate 20KHz.

SIMULATION STUDIES

This section presents simulation results obtained from faulty motor drive for the proposed fault prediction. There are two models one is for electrical fault data and other is for mechanical fault.

Electrical Fault Simulation

Figure 5 is a simulation model of propulsion system of EV using MATLAB/SIMULINK. This model is simulated for the electrical faults in system. Model uses a DC source, six step inverter, BLDC motor, gearbox.

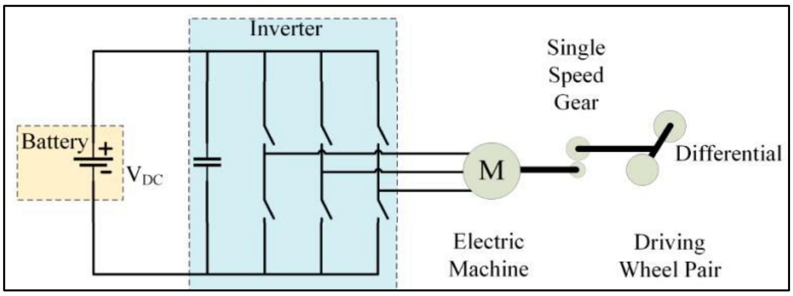

Figure 4: Simulation diagram

This simulation represents a motor running for 0.2s and fault occurs at 0.1s. For battery pack which is a series and parallel combination of Li -ion batteries, a DC source of voltage 300V is taken. The source is then connected to inverter, simulated using six IGBT's. The inverter output is fed to three phase motor's stator windings. The BLDC motor simulated is BLK423S model with parameter mentioned in Table 1. Decoder after the motor to decode the sensor signals and control the gating pulses of inverter.

Parameter	Value
Rated Voltage	310 V
Rated Power	1880 W
Rated Speed	3000 rpm
Rated Torque	6 N-m
Torque constant	136 oz-in/A
Weight	15.87 lbs
Efficiency	96.30%

Table 1: Motor details

When the system is running due to high frequency it is likely to occur fault. Mainly faults are open circuit or short circuit. In inverter the faults are

- One power device open circuit.
- Two power devices open circuited in same arm.
- Two power devices open circuited in different arms.
- Three power devices open circuit.

A total of 24 combinations of open circuit faults are simulated. Using a switch which combines multiple signals to one over a threshold value we are inserting an open circuit fault at 0.1s for each case. The open phase or unbalanced inverter output to the motor produces oscillations which further cause vibrations in the rotor and give abnormalities in the drive's operation.

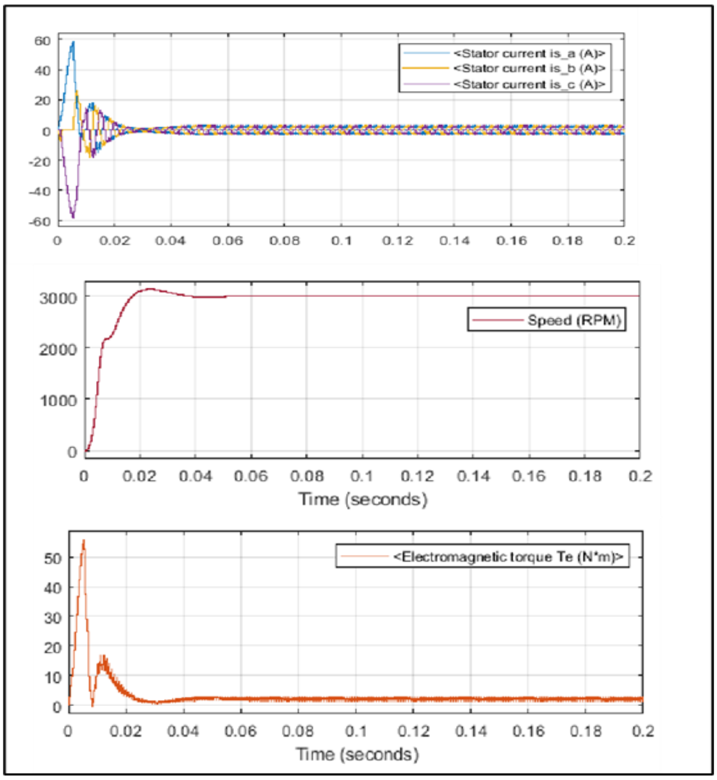

Figure 5: Current, Torque and Speed variations in normal running

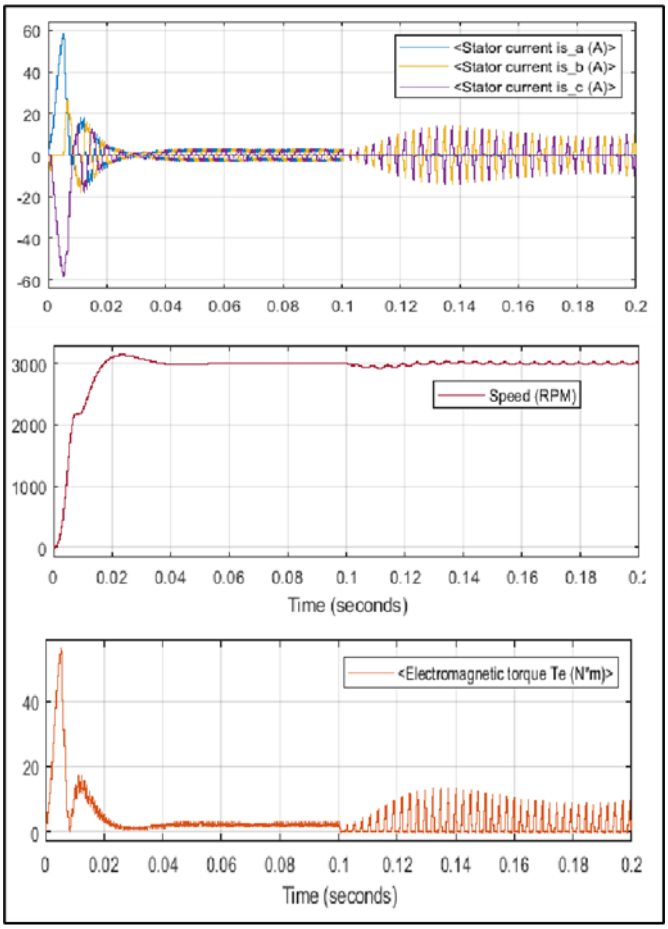

Figure 6: S1 open circuit results

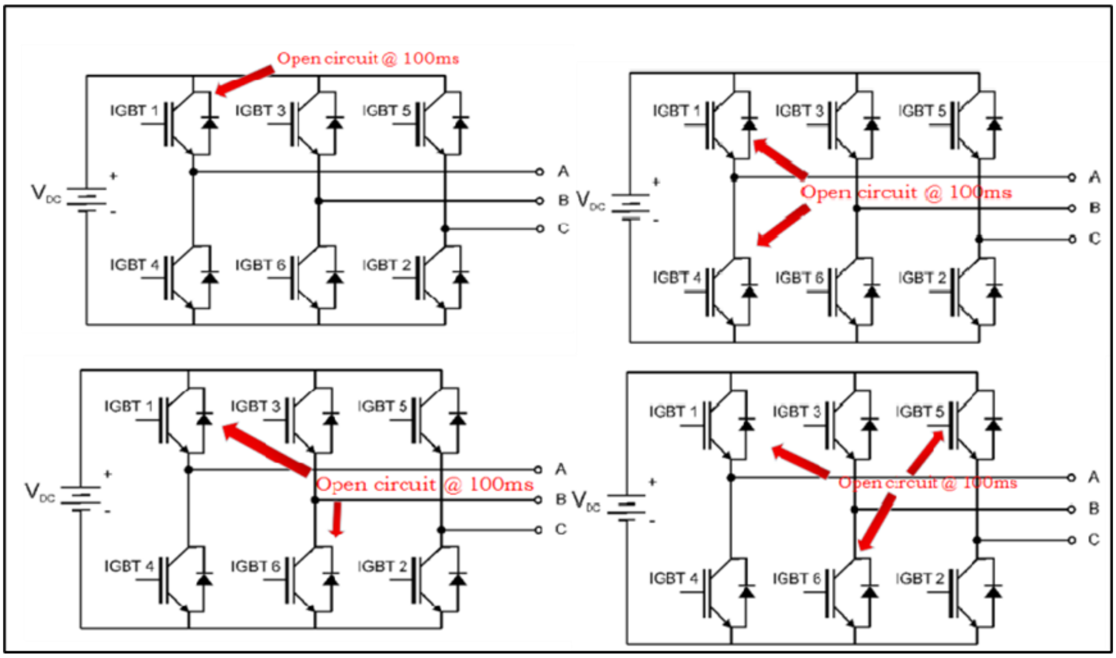

Figure 7: Inverter faulty cases

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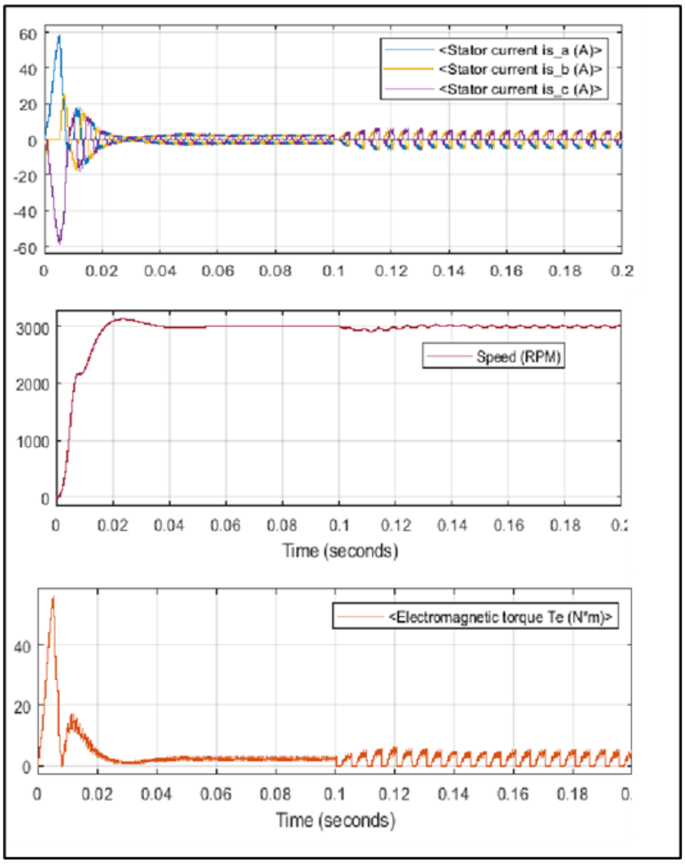

Figure 7: S1 & S4 open circuit results

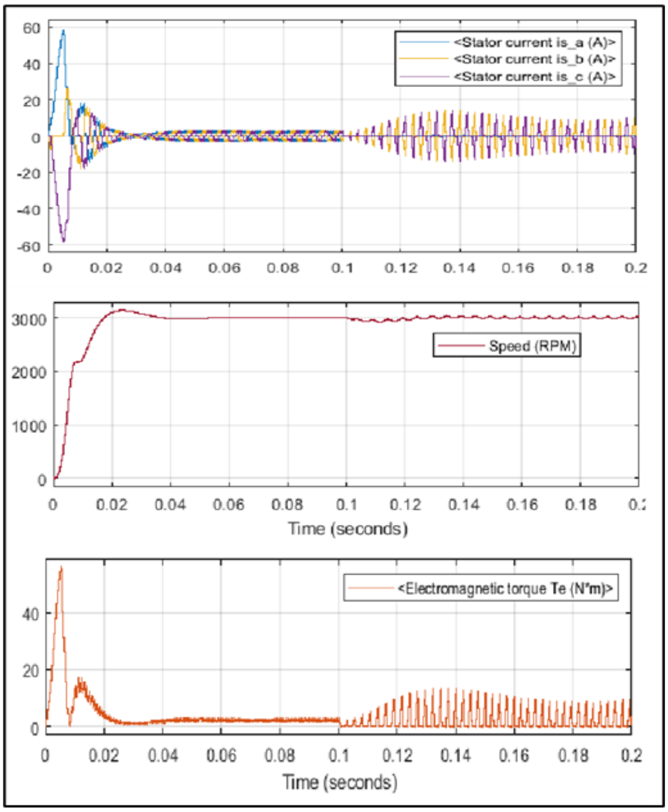

Figure 8: S1 & S6 open circuit

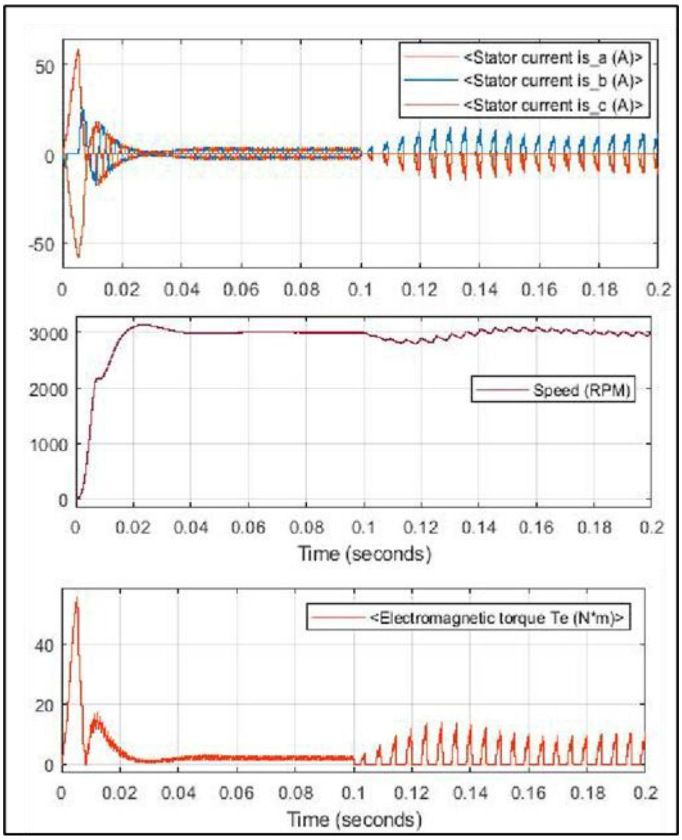

Figure 10: S1, S6 & S5 open circuit (3 phase fault)

Mechanical Fault Simulation

Second, comes the mechanical fault, figure 11 shows the transmission drive which consists of a torque drive, drive shaft, clutch, and high and low gears connected to an output shaft. Fault modelling is done by adding a constant to the vibration sensor for the sensor drift, sdrift=0. This value can be varied for acquiring data for faulty conditions. By varying the sdrift, shaftwear, geartooth gain we created cases. Vibration signals are acquired from the simulation and analyzed. Then a data ensemble is formed which contains various variables for each case of fault. For gear tooth fault condition indicators are identified and the SVM classifier is used to form a model which classifies the gear tooth fault.

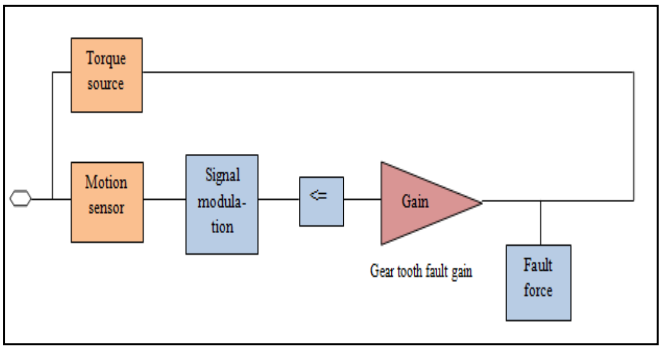

Figure 9: Gear tooth fault modeling diagram

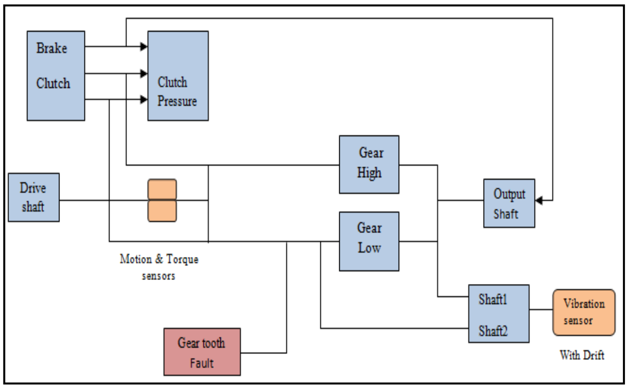

Figure 10: Transmission system simulation

Figure 1 shows the confusion matrix for the prediction model for the gear fault classification. This shows there is one expected fault is predicted as no fault. So this model can be improved by trial and error method (adding or changing the condititon indicators) until there is no error in model.

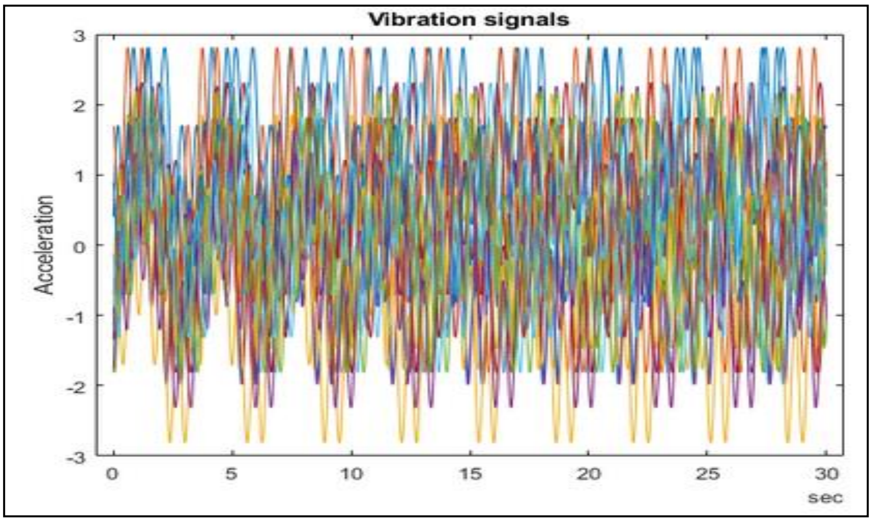

Figure 11: Vibration signals

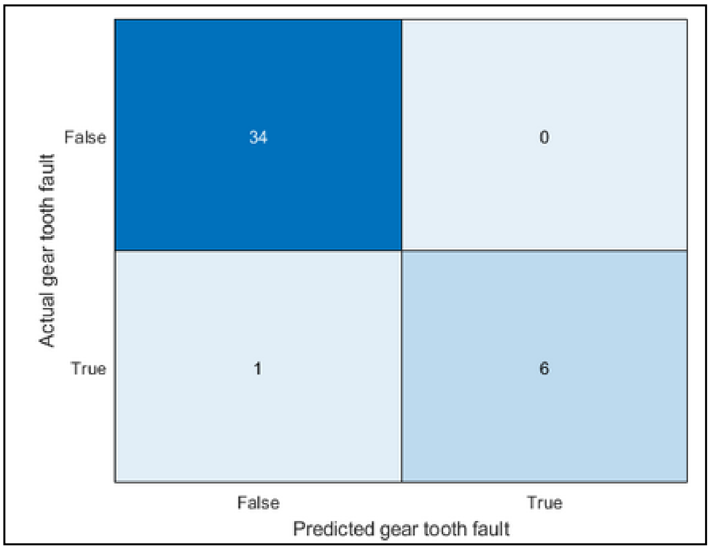

Figure 12: Confusion matrix of prediction model

CONCLUSION

Maintenance of the core components of an electric vehicle is very crucial to ensure productivity, longevity, drive quality, and a safe environment. Predictive Maintenance is an approach that uses the operating & faulty condition data to predict future machine conditions and make decisions upon this prediction. The methodology used for predictive maintenance and condition monitoring can be based on machine learning and data analytics. The process of learning starts with the observation of data and using it in future instances for building the model. The primary aim is to allow the computer to learn without the involvement of the intervention of human assistance. A few machine learning methods are supervised learning, semi-supervised learning, and reinforcement learning. The main aim of the presented research is to use the available sensor data of the electric vehicle from various electronic control units and design a predictive model which classifies the various electrical and mechanical faults that occur in an electric vehicle and predicts the types for increasing the reliability of the whole electrical vehicular system. The workflow of the project is defined as fault modelling, generating healthy and fault data, processing the data using time synchronous averaging, identification of the system condition indicators and finally using these condition indicators, an SVM classification prediction model is designed from which the desired results and conclusion are inferred from the simulation studies.

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