

# Simulation of Incipient Fault Detection, Confirmation and Diagnosis Using Kalman Filter

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**Abstract:** Motor plays a important role in many household and industry applications for example, in robots, printers, etc wherever it is necessary to convert the electrical energy to a mechanical energy. In this paper a model based fault diagnosis, detection and fault confirmation in DC motor is presented. A comparison is made by building a healthy and faulty DC motor. The Kalman filter and its iterations are mathematically modeled and is used for fault diagnosis of DC motor. The performance is evaluated from the estimated states of the Kalman filter. For incipient fault as a Gaussian noise, a fault model is developed and difference between healthy and faulty output of DC motor is obtained. Simulink (Matlab) is the simulation tool used to model the DC motor and Kalman filter. Computer simulation and modeling tools have been widely used to support and enhance the working and operation of electro mechanical devices.

**Keywords:** DC motor, incipient faults, Kalman filter, Simulation and modeling, Fault Detection and Diagnosis.

## 1. Introduction

Motors are used to power many of devices which we use in everyday life. Some of the examples of large motor applications include elevators, electric trains and heavy metal rolling mills. Similarly some applications of small motors are automobiles, robots, toys, hand power tools and food blenders and even in some medical applications also we find the use of motors. Because of such huge applications of DC motors it is necessary to monitor the degradation and life time of healthy operation of the motor.

### A. Need for fault detection

A motor is usually sensitive to kinds of faults occurring at different stage of operation. When one of these faults does occur the operation has to be stopped for a non-programmed maintenance schedule. The cost of this schedule can be high and this justifies the development of fault tolerant motor systems. Fault diagnosis and monitoring are modern ways to increase reliability, and they are possible without installing extra hardware. The reliability improvement of motor operation can be achieved by reliable and high-performance fault diagnosis schemes for these faults.

### B. Fault detection and diagnosis

Fault detection and fault diagnosis plays a very vital role in monitoring the product quality, automatic control systems and in safety and critical processes. Researchers in different disciplines such as medicine, engineering, science, business, and finance have been developing methodologies to detect fault (failure) or anomaly conditions, pinpoint or isolate which component/object in a system/ process is faulty, and decide on the potential impact of a failing or failed component on the health of the system. Fault Detection and Diagnostic (FDD) techniques like current signature analysis, thermal analysis and vibration monitoring are used to identify faults in electric machines typically in motors [1].

Detecting, isolating, and identifying an impending or incipient failure condition, the affected component or subsystem or system is still operational even though at a degraded mode is defined as fault diagnosis. Fault (failure)

detection or fault diagnosis is aimed at determining accurately and without false alarms impending or incipient failure conditions. The objective of FDD [2], is to achieve the best possible performance of a given diagnostic model by minimizing false positives and false negatives while reducing the time delay between the initiation and detection/isolation of a fault event. Thus in this paper a model based incipient fault detection and fault confirmation in DC motor is build using Simulink with Kalman filter.

## 2. Model-Based Fault Detection Methods

Model-based methods [3], [4], and [5] rely on the availability of a good dynamic model of the system. The model is used throughout the four stages of development: Research, Design, Implementation and Verification and validation. Model based system design is the use of models to describe the specifications, operation, and performance of a component or a system of components. In this paper model based fault detection algorithm is employed which is based on state observers using Kalman filter. The comparison of the estimated state variable and actual measurements, provide the information required to check the nature of faults. The variations in the residues thus generated, are used for detecting and identifying and quantifying of faults.

### A. Methodology

In this paper a model of healthy and a faulty DC motor is built using Simulink. Incipient fault as white (Gaussian) noise is inserted into the functional model of DC motor and output of both model are analysed as shown in the fig(1). Using Kalman filter [6], [7], [8] estimation error between healthy and fault motor is analyzed. Along with estimation, error covariance is also presented. The below chart shows the flow of implementation carried for the detection and confirmation of the incipient faults in the DC motor.

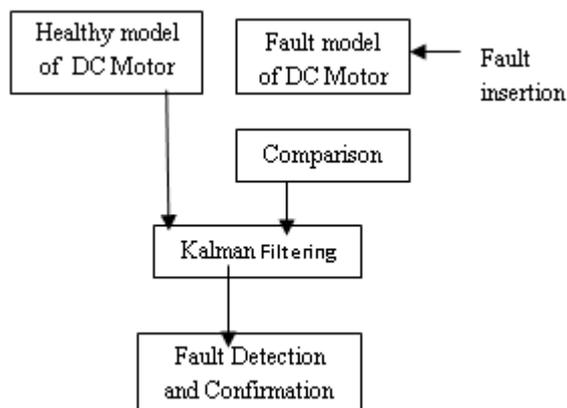


Figure 1: Proposed model of fault detection and confirmation

**B. Mathematical model of DC Motor**

DC motors consist of one set of coils, called an armature, inside another set of coils or a set of permanent magnets, called the stator. Applying a voltage to the coils produces a torque in the armature, resulting in motion. It design to run on DC electric power which uses electrical energy and produce mechanical energy. Modeling of the DC motor is built by considering the specifications of 12V DC motor [9].

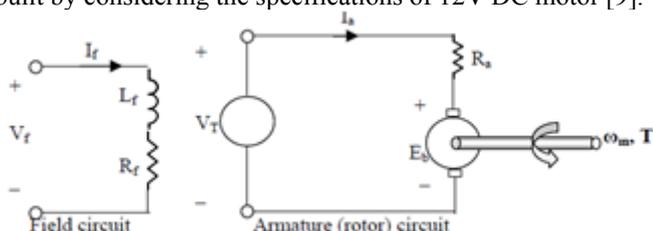


Figure 2: Physical model of Dc Motor

The schematic diagram of functional model of a DC motor built using Simulink is shown in figure (3). A DC motor [10] has two distinct circuits: Field circuit and armature circuit. The input is electrical power and the output is mechanical energy.

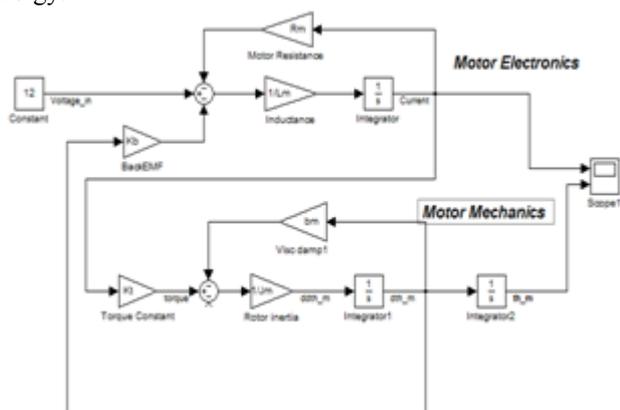


Figure 3: Functional model of DC Motor using Simulink

The functional model of DC motor is built based on the following equivalent equations of the DC motor as referred from the [11].

$$\frac{di}{dt} = \frac{V}{L_m} - \frac{R_m}{L_m} i - \frac{K_t}{L_m} \omega \text{-----(1)}$$

$$\frac{d\omega}{dt} = \frac{K_b}{J_m} i - \frac{B_m}{J} \omega \text{-----(2)}$$

The input is 12 V dc, with 4850 rpm 10 Watt DC motor is built using Simulink and the output considered here is current, velocity and speed of the DC motor. The following are the DC motor values consider for modeling using simulink.

- R<sub>m</sub> = 2.18 Ω, Armature resistance;
  - L<sub>m</sub> = 0.238 mH, Inductance
  - K<sub>b</sub> = 0.02352, Back EMF constant (Volt-sec/rad)
  - K<sub>t</sub> = 0.0235, Torque constant (Nm/A)
  - J<sub>m</sub> = 1.07e-6, Rotor inertia (Kg /m<sup>2</sup>)
  - B<sub>m</sub> = 12e-7, Mechanical damping factor
- I<sub>a</sub> is the armature current and ω is the rotor speed,

For continuous time system, considering the above DC motor parameters the linear response of the current output, velocity and speed of the DC motor are obtained after simulation as shown in the bellow figure(4).

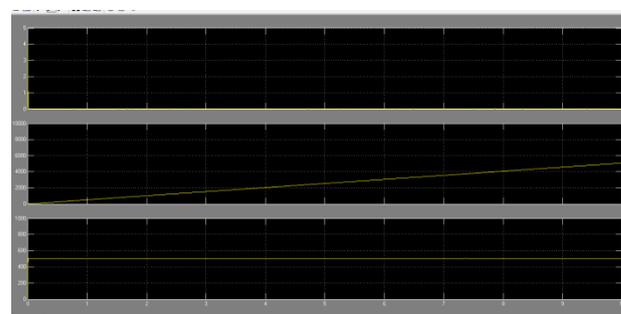


Figure 4: Current, velocity and speed output of healthy DC motor

**C. Faults in DC Motors**

DC motors are susceptible to many types of fault in industrial applications. A motor failure that is not identified in an initial stage may become catastrophic and the DC motor may suffer severe damage. Thus, undetected motor faults may cascade into motor failure, which in turn may cause production shutdowns. Such shutdowns are costly in terms of lost production time, maintenance costs, and wasted raw materials. Several alternatives have been used in industry to prevent severe damage to DC motors for different faults and to avoid unexpected production shutdowns. Most maintenance must be performed with the motor turned off, which also implies production shutdown. Usually, large companies prefer yearly maintenance in which the production is stopped for full maintenance procedures. Hence methods of fault detection and diagnosis are necessary for uninterrupted operation of motors.

**3. DC Motor Fault Insertion and Confirmation**

**A. Discrete model of DC motor**

Discretised state space representation of DC motor using equations 3 and 4 is modeled in Simulink, considering current and speed as its two states.

$$X(k+1) = A x(k) + B u(k) \text{-----(3)}$$

$$Y(k) = C x(k) + D U(k) \text{-----(4)}$$

For sampling time of 10 microsec the discrete time state space model of DC motor is as shown below.

$$A = \begin{bmatrix} -0.0344 & -0.0007 \\ 1.6343 & 0.0300 \end{bmatrix} \quad B = \begin{bmatrix} 0.0334 \\ 41.0557 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \text{ and } D = 0$$

**B. Application of Kalman filter to DC motor:**

Kalman filter is an optimal (linear) estimator or optimal recursive data processing algorithm which belongs to the state space model(time domain) compared to frequency domain. The Kalman filter helps to estimate past, present and future state behavior of the system. The process of use of Kalman filter for DC motor is as shown in the below figure (5).

Kalman filter is an optimal state observer which is used mainly for state estimation when the output measurement data of the system, is corrupted by random noise, which is Gaussian.

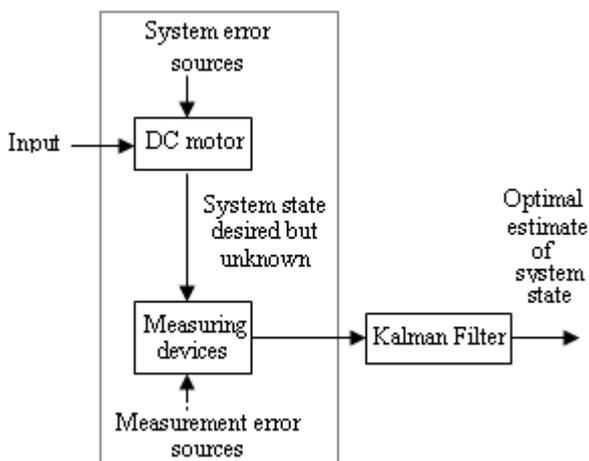


Figure 5: Implementation of Kalman Filter

In this present work the output armature current of DC motor is considered as measurement data. Incipient fault as Gaussian noise/ white noise is inserted as measurement and process noise. The Kalman filter equations are represented as,

The system state equation of Kalman filter is as shown below:

$$x_k = A_k x_{k-1} + B_k u_k + w_{k-1}$$

$$y_k = C_k x_k$$

$$\tilde{y}_k = y_k + v_k$$

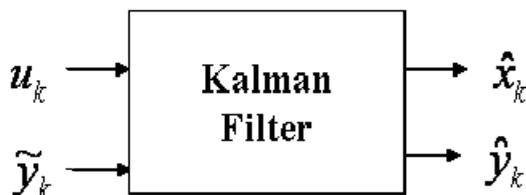


Table 1: Kalman Filter equations

Time Update (prediction)	Measurement Update (correction)
$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k$	$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$
$P_k^- = AP_{k-1}A^T + Q$	$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-)$
	$P_k = (I - K_k H)P_k^-$

The above table 1 shows the time update and measurement update equations,

- Where,
- $K_k$  = Kalman gain
- $P_k$  = Covariance
- $W_{k-1}$  = Process noise
- $V_k$  = Measurement noise
- $Q$  = Process covariance noise
- $R$  = Measurement covariance noise

**C. Proposed model of DC motor with Kalman filter**

The proposed fault detection and confirmation model estimates the state outputs of the DC motor by eliminating the noise inserted using the Kalman filter as shown in the simulink model of figure(6) and (7).

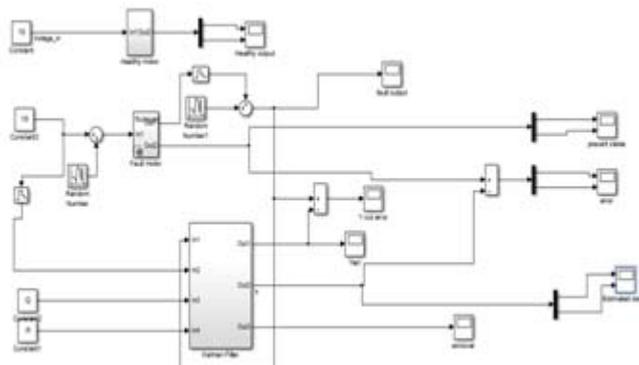


Figure 6: Simulink model of proposed system

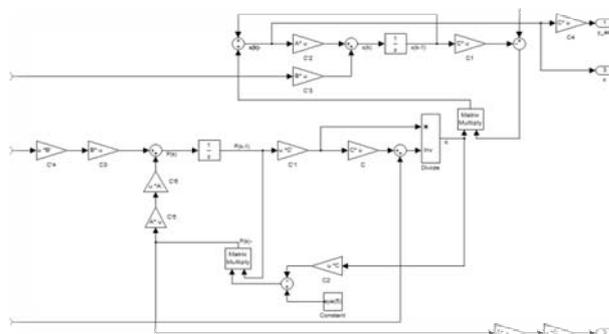


Figure 7: Simulink model of Kalman filter

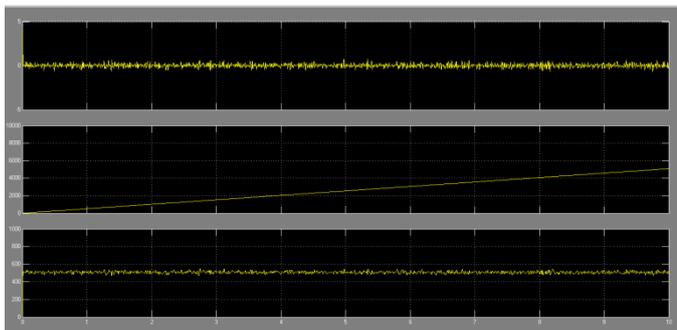


Figure 8: True states output Current and speed of DC motor

The above figure (8) shows true state output with the presence of Gaussian noise in the current output.

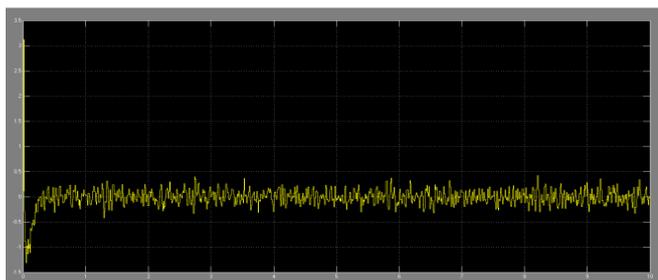


Figure 8: Difference between the healthy and faulty output

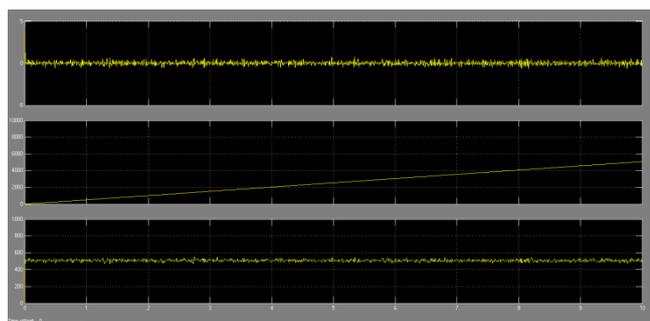


Figure 9: Estimated states output Current, speed and velocity of DC motor

#### 4. DC Motor Parameters and Faults

Table 2 shows the different parameters with its specifications and importance. As mentioned in paper [12] the parameters such as friction coefficient and armature resistance are used to create the bearing fault and armature winding fault respectively. The increase in bearing fault is simulated by increase in the friction coefficient and the increase in armature winding fault is simulated by decrease in armature resistance.

Table 2: Importance of DC motor parameters

Parameter	Definition	Comment
$K_e$	Back-EMF constant	Dominate factor in determining motor's steady state speed for a given voltage
$K_t$	Torque Constant	Determines motor's required current for a given torque output
$R_a$	Terminal Resistance	Determines how much power will be dissipated in the motor for a given current level
$L_a$	Armature Inductance	Determines how fast current to the motor can be turned on
$J$	moment of inertia of the rotor	A measure of an object's resistance to changes in its rotation rate
$B$	Viscous Friction (Damping)	A measure of dynamic friction

Armature winding fault confirmation is modeled by varying the armature resistance of the DC motor using simulink. The output current value changes for the different values of armature resistance. The following are the results obtained for 10%, 25% variation in resistance value. When armature resistance is varied by 10% i.e.  $2.266\Omega$  and 25% i.e.  $2.575\Omega$ , current output is as shown in figure (10) and (11) respectively.



Figure 10: Current output for 10% of armature winding fault

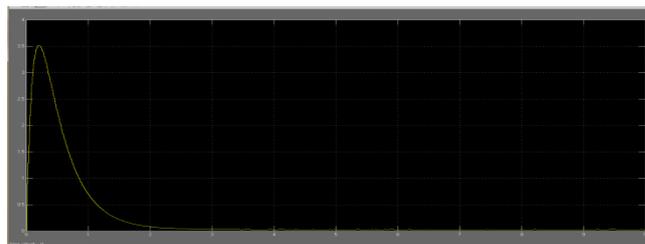


Figure 11: Current output for 25% of armature winding fault

Similarly the bearing fault confirmation is modeled by varying the value of friction coefficient of DC motor using simulink. The output current settling time varies for different values of friction coefficient. The following are the results obtained for 10%, 25% variation in the damping ratio value. When the damping ratio value is varied by 10% i.e.  $b_m = 13.2e-7$  and 25% i.e.  $b_m = 15e-7$  the current response of the DC motor is as shown in figure (12) and (13) respectively.

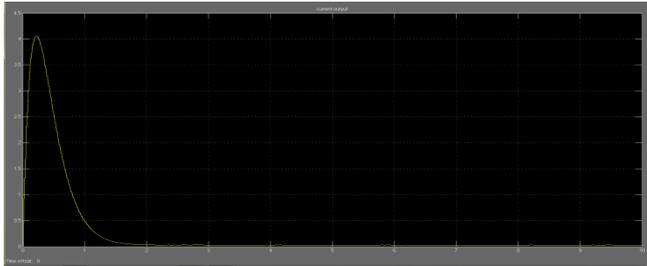


Figure 12: Current output for 10% of bearing fault

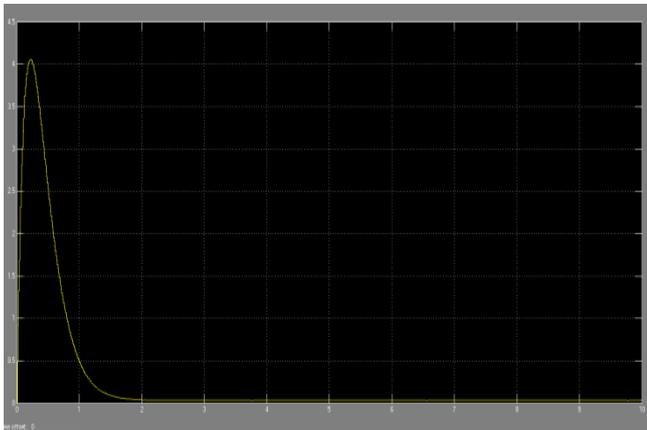


Figure 13: Current output for 25% of bearing fault

## 5. Conclusion

The continuous healthy operations of machines and motors are critical for the reliability of the entire system. Effective FDD can detect and diagnose abnormal conditions in time, and thus reduce the chances of catastrophic failures. In this paper a fault DC motor model design is presented for fault analysis and fault confirmation from which one can analyze the remaining useful life behavior and operation of the motor. Also a model based technique for quantification and identification of the bearing and armature winding faults in DC motor is presented in this paper. A linear iteration Kalman filter is designed for the estimations of the two states of the DC motor i.e. current and speed when noise as fault is inserted into the system. With these basic fault detection and confirmation one can diagnosis the healthy condition and operation of the motor. This method of fault detection has the advantage that it is good for measurement uncertainties. The Kalman filter has shown good performance and the other variants have not made any variations even in faulty conditions for the consider DC motor. The proposed methodology is able to quantify the level of faults in addition to identifying the fault by analyzing startup transient current from DC motor, which is different from previously proposed methodologies or expert systems that only identify the faults.

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