# Fault Detection of PMSMs using IMM Strategy

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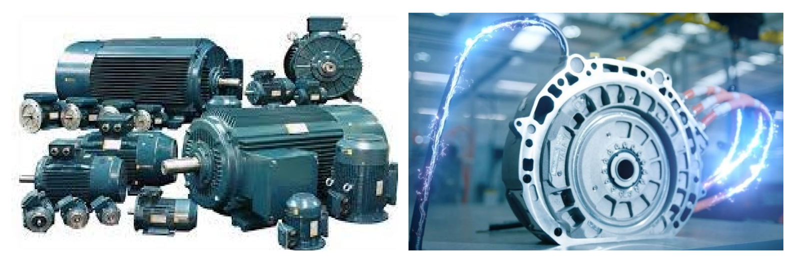
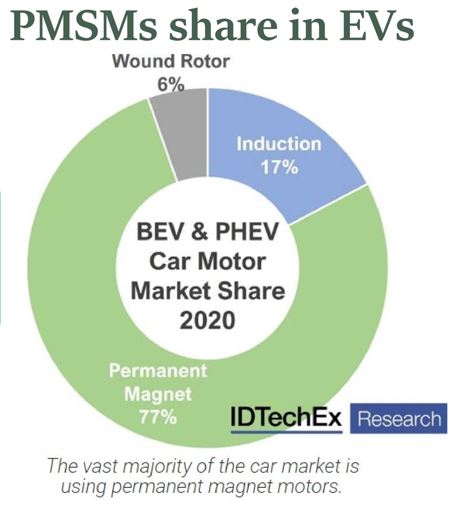
**EECOMOBILITY (ORF) & HEVPD&D CREATE**

## Why Permanent Magnet Synchronous Motors (PMSM)?



- *Efficiency*: PMSM: 92-97%, IM: 80-90%, SRM: 93%
- *Power to Mass Density:* PMSM: 8kW/kg, IM: 2 to 3 kW/kg, SRM: 5 kW/kg
- *More precise speed control*
- *Reduced operating temperature*

PMSMs share in EVs



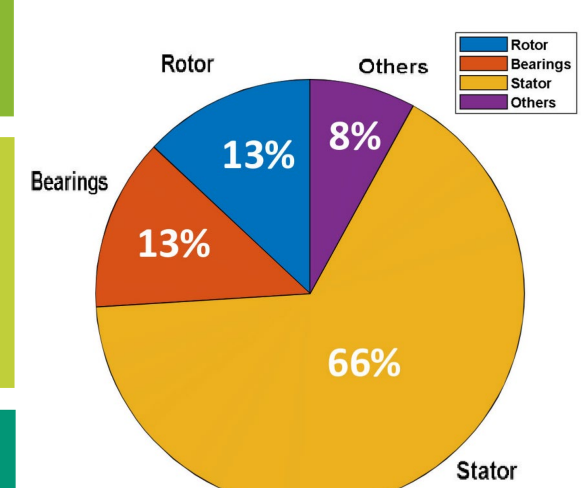

The vast majority of the car market is using permanent magnet motors.

## Different Faults In PMSMs

***Mechanical Faults***
- I) Bearing Faults
- II) Eccentricity Fault

***Electrical Faults***
- I) Inter-turn Short-Circuit
- II) Phase to Phase/Ground short circuit
- III)Phase Open Circuit

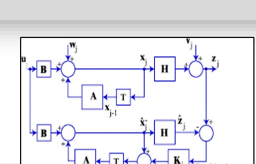
***Magnetic Faults***
- I) Demagnetization Fault




## Fault Detection Methods in PMSMs

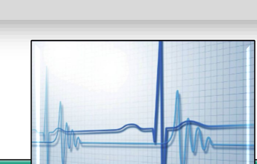
**Data-Driven Methods (AI)**

- Collecting a sufficient amount of data is difficult.
- Applicable for almost all kinds of faults
- Can extract features artificially or automatically to realize fault and health status identification



**Model-Based Method**

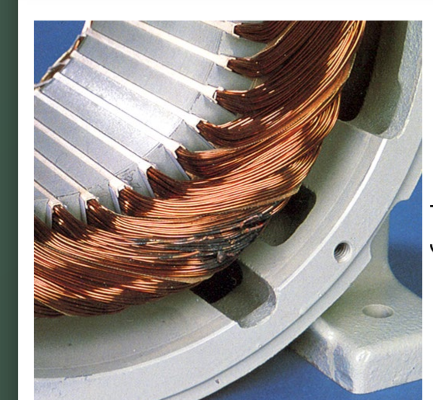
- Requires the establishment of a high-precision model
- Usually can introduce a fault indicator.
- If models are not precise, failure in fault detection

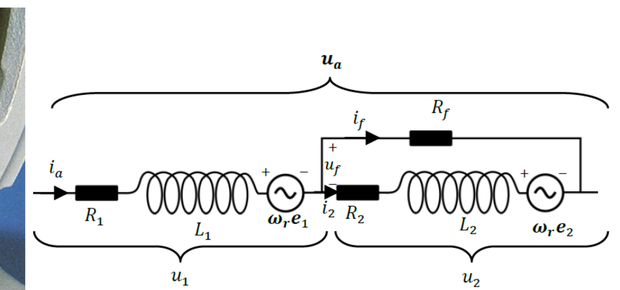


**Signal Processing Methods**

* Uses frequency spectrum analysis like Fast Fourier transform for the sampled signal
* Not suitable for variable speed and load conditions like EV motors.
* Complex methods require lots of computational costs

## Model of PMSM with Inter-Turn Short Circuit (ITSC) fault

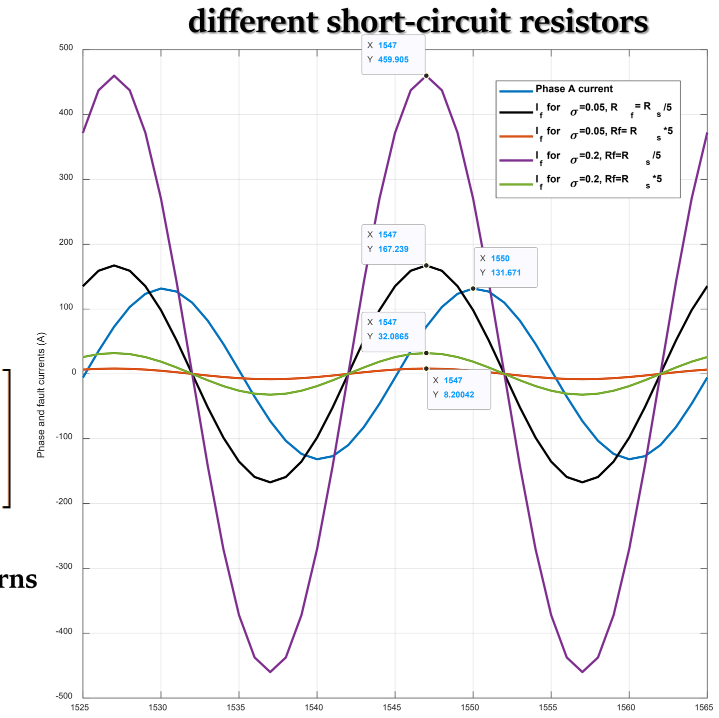





$$\begin{bmatrix} u_a \\ u_b \\ u_c \\ u_f(=0) \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 & -\sigma R_s \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_s & 0 \\ -\sigma R_s & 0 & 0 & \sigma R_s + R_f \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix} + \begin{bmatrix} L & M & M & -(M_{1f}+L_f) \\ M & L & M & -M_{bf} \\ M & M & L & -M_{cf} \\ -(M_{1f}+L_f) & -M_{bf} & -M_{cf} & L_f \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix} + \omega_r \begin{bmatrix} e_a \\ e_b \\ e_c \\ -e_f \end{bmatrix}$$

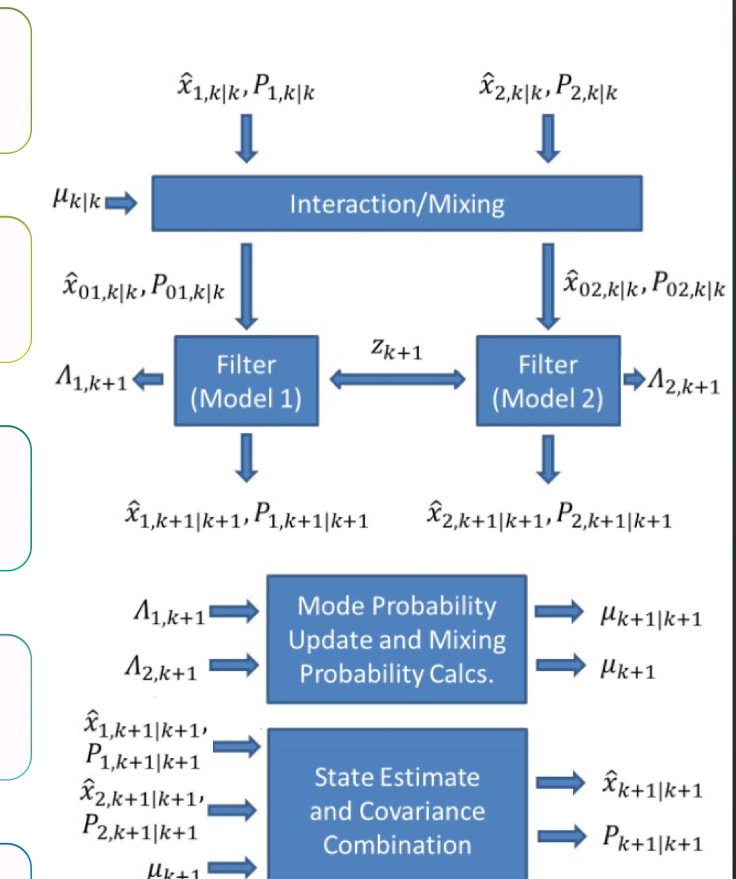
**σ: Ratio of the number of short-circuited turns to the total number of turns**
**$R_f$: short-circuit resistors**

**Phase and fault currents for different numbers of short-circuited turns and different short-circuit resistors**




## IMM Strategy For Fault Detection

- ***Model selection*** — Extract several models for healthy and faulty conditions
- ***Filter design*** — Select appropriate filters (Kalman or SVSF) for extracted models
- ***Mode probability computation*** — Calculate the probability that the system is in a particular model at a given time, based on measurements
- ***Mode estimation*** — Estimate the system's mode based on the mode probability computed
- ***State estimation*** — States of the system are estimated using the filter associated with the estimated mode.




## Parameter and state estimation simultaneously

**Some parameters in the model are unknown when a fault happens. These parameters need to be estimated with the states of the system at the same time. Equations of the system can be rewritten as:**

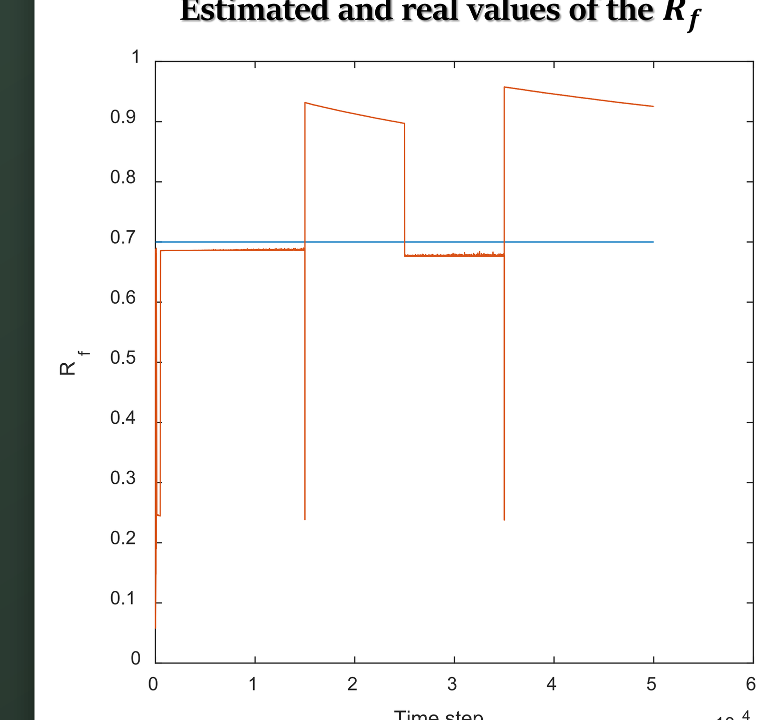
$$\begin{cases} \dot{X}_e(t) = \begin{bmatrix} \dot{X}(t) \\ \dot{\lambda}(t) \end{bmatrix} = \begin{bmatrix} A(\lambda(t)) & 0 \\ 0 & 0 \end{bmatrix} . \begin{bmatrix} X(t) \\ \lambda(t) \end{bmatrix} + \begin{bmatrix} B(\lambda(t)) \\ 0 \end{bmatrix} .U(t) + \begin{bmatrix} W_X(t) \\ W_\lambda(t) \end{bmatrix} \\ Y(t) = C(\lambda(t)).X(t)+D(\lambda(t)).U(t)+V(t) \end{cases}$$

*To estimate one or several parameters (λ) of the model*

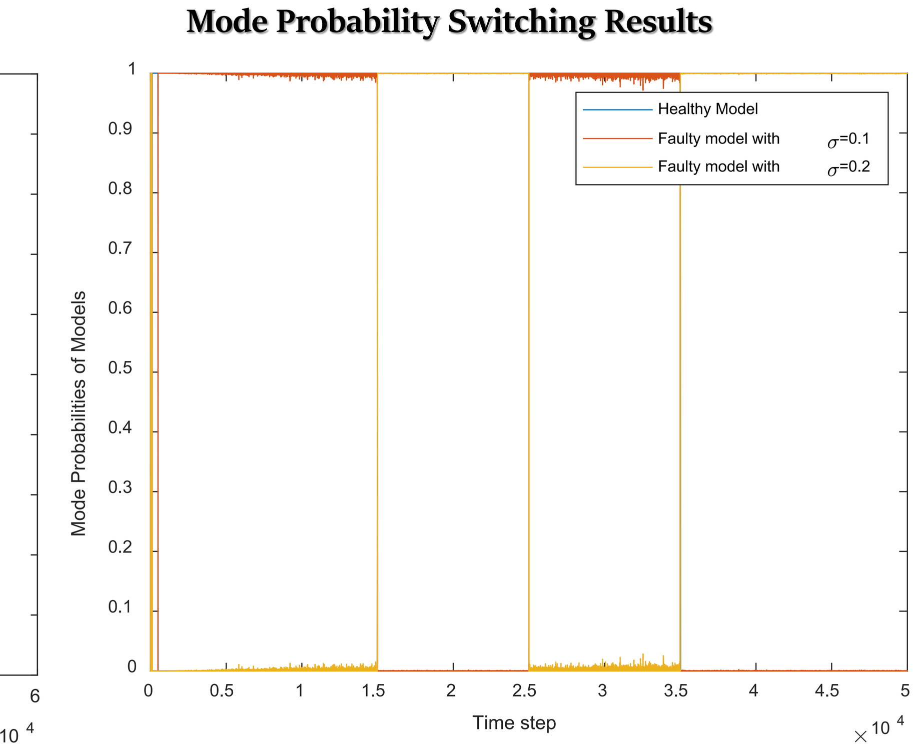
## Simulation Results

**Three models for fault detection are considered. One for the electric motor in healthy condition and two for faulty conditions with different fault severity. Process or real system has a fault with different severity and switches between different fault severity conditions at sample times equal to 200, 1500, 2500, and 3500. corresponding Extended Kalman Filter (EKF) is designed and used for each one of these models. As presented in the following figures, Interactive Multiple Model (IMM) is able to detect the fault occurrence in a reasonable number of time steps.**

**Estimated and real values of the $R_f$**




**Mode Probability Switching Results**




**The results of the IMM-Kalman filtering need to be compared with IMM-Smooth-Variable Structure Filter (SVSF) since that method is more robust to uncertainty in the models.**
**Also, all results need to be evaluated using a real PMSM setup which provides access to the middle point of the winding and enables emulating ITSC fault by using an external resistor.**

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