Amplification of Single Mechanical Fault Signatures Using Full Adaptive PMSM Observer

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This paper presents a localized mechanical fault detection method using a full adaptive permanent magnet synchronous machine (PMSM) observer in a d/q reference frame.

To study the influence of the adaptive PMSM observer gains on fault signatures, the observer model is first of all linearized at an operating point.

A dedicated experimental setup based on an original mechanical fault emulator and a 7.8 kW PMSM drive is designed to validate the simulation results.

The simulation and the experimental results show that the proposed method is effective to amplify single mechanical fault signatures and the calculated fault indicator.
Index Terms

- Adaptive observer design
- fault diagnosis
- permanent-magnet synchronous machine (PMSM)
- signature amplification
- single mechanical fault
The research shows that electro-mechanical systems which are subjected to multiple failures because the often employed in very rough conditions.

The failures occur at stator, in the rotor, in the bearings, or in the gearbox.

Mechanical faults accounts for two-thirds of motor failures.

Monitoring amplitude and frequency of the current signals, fault signatures could be tracked easily.

Monitoring amplitude and frequency of the current signals, fault signatures could be tracked easily. It is well established that the frequency is the signal containing the more information about the fault.
In the case of localized faults, the faults components are produced at predictable side bands frequencies related to the current frequency.

The amount of the fault can be determined by amplitude in the current signal.

However low fault cannot be always detected due to its low amplitude.

This paper presents a localized fault diagnosis using an adaptive observer i.e., PMSM observer in the \{d/q\} frame which is performed to highlight signatures in the motor mechanical speed in order to overcome the low fault signatures amplitude in the case of low degradation.

Tests are carried out on an original test bench which was designed to simulate localized faults, such as gears and bearings faults.
Procedure

- The fault sensitivity of PMSM stator currents and rotor speed measurements is very low with regard to single mechanical faults.
- The amplification of single mechanical fault signatures in frequency domain is proposed by adjusting the adaptive PMSM observer gains.
- Then, the static gain, the resonance, and the quality factor Q of different transfer functions are analysed.
- A experimental setup based on an original mechanical fault emulator and a 7.8 kW PMSM drive is designed to validate the simulation results.
- The simulation and the experimental results show that the proposed method is effective to amplify single mechanical fault signatures and the calculated fault indicator.
In this section mechanical fault characteristic frequencies expressions are defined.

Single or localized faults are generally referred to single bearing faults or tooth fault in gearboxes.

This kind of failure generates an abnormal load affecting the machine torque.

The load torque is written as

$$\Gamma_{load}(t) = \Gamma_0 + \delta \Gamma(t)$$

Where, $\Gamma_0$ = constant component,

$\delta \Gamma(t)$ = disturbance torque
In this paper, the additional torque $\delta \Gamma(t)$ is modeled as a periodic impulse signal with a periodicity related to the mechanical position ($\theta_m$). The disturbance torque $\delta \Gamma(t)$ is written using its Fourier series as

$$\Gamma_{load}(t) = A \times D \left[ 1 + 2 \sum_{n=1}^{\infty} \left( \frac{\sin(n\pi R)}{n\pi R} \right) \cos(n\theta_d) \right]$$

The following mechanical equation traduces the transfer of torque variations to the rotation speed signal:

$$w_m(t) = \frac{1}{J_m} \int_{t_0}^{t} (\Gamma_{motor}(\tau) - \Gamma_{load}(\tau))d\tau$$
There are 3 parts in PMSM observer:

- PMSM model.
- Adaptive Observer.
- Linearization of Adaptive Observer.
The stator equation of the sinusoidal PMSM in parks (d/q) reference frame fixed to the rotor is modeled as:

\[ u_s = R_s i_s + \psi_s + \omega J \psi_s \]

The stator flux is written as:

\[ \psi_s = L i_s + \psi_{pm} \]

The electromagnetic torque is given by:

\[ T_e = \frac{3}{2} p \psi_s^T J^T i_s \]
Adaptive Observer

- The rotor speed and position estimation in adaptive observers is based on the error estimation between the measured stator currents and the estimated ones.

- The adjustable model is fed back by the output of the adaptation mechanism, i.e., the rotor speed in the present case.

- The adaptive model can be written as:

\[ \dot{\hat{\psi}_s} = u_s - R_s \hat{i}_s - \hat{\omega} J \hat{\psi}_s + \lambda \ddot{i}_s \]
A linearization at an operating point of the observer model is performed using the adaptation law. The state vector $x$ can be written as

$$x = x_0 + \delta x$$

The linearized model can be defined as

$$\frac{d}{dt} \begin{bmatrix} \delta \hat{id} \\ \delta \hat{iq} \\ \delta \hat{\omega} \end{bmatrix} = \begin{bmatrix} A \end{bmatrix} \begin{bmatrix} \delta \hat{id} \\ \delta \hat{iq} \\ \delta \hat{\omega} \end{bmatrix} + \begin{bmatrix} B \end{bmatrix} \begin{bmatrix} \delta v_d \\ \delta v_q \\ \delta \hat{id} \\ \delta \hat{iq} \\ \delta \hat{\omega} \end{bmatrix}$$

The linearized model can be defined as

$$y = \begin{bmatrix} C \end{bmatrix} \begin{bmatrix} \delta \hat{id} \\ \delta \hat{iq} \\ \delta \hat{\omega} \end{bmatrix}$$
The value of $A$, $B$ and $C$ are given as follows

$$A = \begin{bmatrix} -\frac{R_s}{L_d} - \lambda_1 & \frac{L_q}{L_d} w_0 + \lambda_2 & \frac{L_q}{L_d} i q_0 \\ -\frac{L_d}{L_q} w_0 - \lambda_2 & -\frac{R_s}{L_q} - \lambda_1 & \frac{\psi_{pm}}{L_q} - \frac{L_d}{L_q} i d_0 \\ -a_1 & -a_2 & -a_3 \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{1}{L_d} & 0 & \lambda_1 - \lambda_2 & 0 \\ 0 & \frac{1}{L_q} & \lambda_2 & \lambda_1 & 0 \\ 0 & 0 & a_1 & a_2 & a_3 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 \dot{0} & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$
The transfer function between the measured and estimated variable is given by

$$ F = C(sI - A)^{-1}B = \begin{bmatrix} F_{11} & F_{12} & \cdots & F_{15} \\ F_{21} & F_{22} & \cdots & F_{25} \\ F_{31} & F_{32} & \cdots & F_{35} \end{bmatrix}. $$

Fig. 2. Bode diagram of the function $F_{34}(s)$ for $\lambda_1 = 15$, $\lambda_2 = 0$, $k_i = 100$ and $k_p = -0.05$. 
They have divided the estimated study in 3 types:

- Transfer Function Analysis
- Observer Design
  - Parameter A.
  - Parameter B.
- Simulation Results
The transfer function between the stator current $i_q$ and the estimated speed $\dot{w}$ is written as:

$$F_{34}(s) = \frac{\dot{w}(s)}{i_q(s)} = \frac{a_{34.2} s^2 + a_{34.1} s + a_{34.0}}{b_3 s^3 + b_2 s^2 + b_1 s + b_0}$$

The chosen operating point corresponds to 20% of the nominal rotation speed.

With a constant speed $w_0$, the current $i_q$ will be constant.

Bode diagram of the function $F_{34}(s)$ is plotted in three different cases. In each case, two parameters are kept constant and the third one varies. Figs. 3, 4, and 5 show the obtained results.
In Fig. 3, it can be noted that the parameter $k_i$ affects the resonance frequency and the static gain of the filter. For $k_i = 50$, the resonance frequency corresponds to 36 Hz and for $k_i = 100$, the resonance frequency increases to 50 Hz.
Fig. 4, the parameter $k_p$ influences both the static gain and the $Q$ factor (quality factor or the damping coefficient of the filter). For $k_p > 1$, the resonance disappears.
Fig. 5 shows the influence of $\lambda_1$. It can be noted that increasing this parameter reduces the filter damping without modifying the static gain.
Table I resumes the different parameters interactions with the static gain and $Q$ factor. It should be noticed that $k_i$ is the only parameter which can modify the resonance frequency of the filter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gain</th>
<th>Resonance Frequency</th>
<th>$Q$ factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_i$</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$k_p$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>✓</td>
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The influence of the parameters $k_i$, $k_p$, and $\lambda_1$ on the components $F_{ij}(s)$ ($i = 1,2,3$ and $j = 3,4,5$) are the same as $F_{34}(s)$. It means that the observer is reacting as a low-pass filter with a resonance frequency.
In the previous section, it was demonstrated that amplifying a specified frequency band with a suitable choice of the observer gains is possible. The observer gains setting cannot be performed by taking into account this only criterion since the observer convergence also has to be ensured.

From the state matrix $A$ defined as

$$A = \begin{bmatrix}
-\frac{R_s}{L_d} - \lambda_1 & \frac{L_q}{L_d} w_0 + \lambda_2 & \frac{L_q}{L_d} i q_0 \\
-\frac{L_d}{L_q} w_0 - \lambda_2 & -\frac{R_s}{L_q} - \lambda_1 & \frac{\psi_{pm}}{L_q} - \frac{L_d}{L_q} i d_0 \\
-a_1 & -a_2 & -a_3
\end{bmatrix}$$
the filter resonance frequency can only be adjusted by the gain $k_i$.

So, the following strategy can be proposed for the observer synthesis. They are:

- The parameter $\lambda_1$ is adjusted to obtain the observer desired dynamics.
- The parameter $k_i$ is chosen to coincide with a fault frequency.
- The parameter $k_p$ can be chosen in two ways:
  - To get an acceptable speed dynamics (hence the $Q$ factor will be imposed).
  - To get an optimal amplification of the fault frequencies. In this case, the speed dynamics will be imposed.
Fig. 6 shows in the R/Im plane the observer poles and the PMSM poles in open and current closed loop respectively for $\lambda_1 = 5$. It can be noticed that for this value of $\lambda_1$, the observer dynamics is faster than the PMSM currents dynamics.
Fig. 7 shows the evolution of the sum $G$ for a fault frequency of 22 Hz in function of the two parameters $k_i$ and $k_p$. It can be clearly seen on this figure that four maxima corresponding to $f_d$, $2f_d$, $3f_d$, and $4f_d$ exist.
The block diagram of the PMSM sensorless vector control is shown in Fig. 8. PI controllers are used for the currents and speed loop, respectively. The reference current $i_d$ is imposed to 0.
Fig. 9 illustrates the estimated, the measured, and the reference speed signals, respectively, \( w_m \), \( \omega_m \), and \( \omega_m^* \). We can notice that the estimated speed is able to track the measured one.
Fig. 10 shows the evolution of the estimated speed spectrum when the parameter $k_i$ is varying, which means that the filter resonance frequency is changing.

It can be seen that the estimated speed contains more important fault harmonics than the measured one.

Moreover, the resonance frequency at 45 Hz (for $k_i = 80$) gives a significant fault signatures for the first and second fault frequency ($f_d$, $2f_d$).
Fig. 11 shows that for $k_p = -0.04$ (the value corresponding to the maxima obtained before) the fault frequency components are amplified on the estimated speed.

Fig. 12 shows that for $\lambda_1 = 5$, the fault amplitude increases. However, if the value of $\lambda_1$ increases to ($\lambda_1 = 15$), the fault amplitude decreases.
The authors have divided the experimental section into 3 parts:-

- Test Bench Description.
- Fault Amplification Results.
- Fault Detection Technique.

Test Bench Description.

Fig. 13 illustrates the complete experimental setup which includes two PMSMs. The synchronous motor (PMSM) is driven by a variable-speed drive (VSD). The rotor position (measured by an incremental encoder) is returned directly to the VSD.
The localized fault is emulated using an original mechanical system designed in our laboratory.

The emulator (Fig. 14) is mounted on the coupling motor/generator. It consists of a roller mounted vertically over a nine teeth sprocket. This system emulates a fault occurring nine times per turn.

A spring is mounted above the roller to adjust the force in order to get different fault severities.
Fig. 15. Zoom on the first four faults signatures $f_d, 2f_d, 3f_d,$ and $4f_d$ for the current $i_q$, measured speed $\omega$ with and without fault and the estimated speed $\hat{\omega}$ with fault.
It can be noticed in this figure that the fault amplitude is actually improved in the four cases and especially for \( \text{max}_3 \) and \( \text{max}_4 \), which give the highest magnitude sums.

These results validate the fault signatures amplification and improve the detection of localized mechanical faults.
A simple technique called time synchronous averaging (TSA), which is known for bearing failure detection in electrical machines was used.

By synchronizing a trigger signal with the fault frequency, the TSA just extracts the fault frequencies from the signal and delete all the undesired components.

An estimation technique based on a nonlinear programming is chosen Levenberg Marquardt algorithm.

After the fault frequency estimation, TSA generates a signal which just contains the fault frequencies.
A fault indicator \( \text{ind} \) is calculated for the first four fault frequencies:

\[
\text{ind} = \sum_{n=1}^{4} Y(n \cdot f_d)
\]

Where,

- \( Y(f) \) signal generated by TSA.
- \( f_d \) fault frequency;
- \( n \) fault frequency multiples (here, only the first four fault frequencies are considered).

A second indicator \( R \) is defined: it represents the ratio between \( \text{ind} \) before and after the fault

\[
R = \frac{\text{ind}_f}{\text{ind}_b}
\]
A set of five tests has been realized to illustrate the efficiency of the proposed fault detection procedure and fault indicator.

In this table, it can be seen that the mean value of $R (R_\bar{\ })$ is more important in the four cases for the estimated speed by the observer compared to the measured current $i_q$.
Initially, the observer model was linearized to examine the transfer functions between the estimated state variables and the inputs.

It has been shown that the parameters $k_i$, $k_p$, and $\lambda_1$ influence the fault frequency amplitude.

The parameter $k_i$ affects the resonance frequency which can be chosen as one of the default frequencies $n \cdot f_d$.

The parameter $k_p$ has an impact on the $Q$ factor as well as the static gain. The parameter $\lambda_1$ influences only the $Q$ factor.
The following strategy is proposed to make a judicious choice of these three observer gains:

- $\lambda_1$ is chosen to ensure a faster observer dynamics than the current loop one.
- $k_i$ is chosen to coincide with a fault frequency.
- $k_p$ is chosen so that the sum $G$ corresponds to a maximum.

The fault indicator $R^-$ is improved with the estimated speed compared to the measured current $i_q$.

It can be deduced that the observer output is much richer in terms of fault frequencies amplitude than the input of the observer.

The novelty of this paper is that a speed observer is designed and its gains are adjusted to amplify the localized mechanical fault signatures.


REFERENCES


Thank you for your attention