Reuse of a Damaged Permanent Magnet Synchronous Motor for Torque Ripple and Acoustic Noise Elimination using a Novel Repetitive Observer

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Abstract— A lab-used servo permanent magnet synchronous motor (PMSM) has been accidentally damaged due to overcurrent. On one hand, the mechanical damage in the end bearing and break part generates acoustic noise even when rotating the shaft by hand. On the other hand, the back-emf of the motor becomes unbalanced and exceedingly high torque ripple is produced. Such torque ripple results in intolerable speed ripple and will increase the acoustic noise. This paper aims to reuse this damaged motor by adding a repetitive observer (RO) to the existing speed loop, both the speed control performance and the acoustic noise of the damaged motor can become comparable with its healthy version. The RO is functionally the same as a repetitive controller (RC), but the stability of the RO is independent from the feedback loop, while the stability of RC will affect and be affected by the rest of the system. Therefore, RO can be applied for both the healthy motor and the damaged motor. This work opens the possibility of further enhancing the fault-tolerance ability of a healthy motor or even reusing a damaged motor and still achieve high performance.

Index Terms—Acoustic noise, Fault tolerant, Repetitive observer, Torque ripple reduction, Demagnetization

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) is preferred over the induction motor due to its high efficiency. On one hand, the use of permanent magnet results in the high-power density, on the other hand, the permanent magnet material may suffer from demagnetization as the operation temperature increases. The rise in temperature also brings risks for insulation failures that may lead to inter-turn short circuits or more severe short circuits between phases and phase to ground. According to [1, 2], 38% of all motor faults are stator faults, and the inter-turn faults are most likely to happen. If either the demagnetization or inter-turn fault happens, harmonics in dq -axis flux linkage will occur. Such harmonics will eventually produce torque ripple. Besides the electrical faults, mechanical faults like bearing faults share 40-50% of all motor faults [3].

Both the electrical and mechanical faults can produce acoustic noise. On one hand, the mechanical faults can lead to more electrical faults. On the other hand, the electrical faults can deteriorate the mechanical faults and increase the acoustic noise.

To prevent the demagnetization from happening, many demagnetization models have been proposed to allow online monitoring of the magnets. The comparison work is available in [4]. Authors in [5] proposed a method to detect demagnetization by acoustic noise. The vibration is used in [6] to monitor the partial demagnetization and inter-turn short circuit faults.

A lab-used permanent magnet synchronous motor (PMSM) for servo application has been damaged accidentally due to overcurrent. As a result, its back-emf has become unbalanced, and due to the mechanical damage in its end bearing and break part, an acoustic noise is produced even when spinning the rotor by hand. When rotating this motor under speed control, exceedingly high second order harmonics are produced in torque and thus in speed. Such speed ripple leads to intolerable acoustic noise.

In general practice, once such faults have happened, the damaged motor is normally replaced and disposed. It is barely discussed in existing literature if the damaged motor can be reused with proper compensations, without introducing redundancy [7, 8].

Hence, the aim of this paper is to reuse this motor by applying the recently developed repetitive observer (RO) [9] to smooth the speed and reduce acoustic noise. RO is considered suitable for this application because of the following benefits:

- RO is functionally the same as a repetitive controller (RC) [10, 11], which is a promising tool that can self-learn the periodic disturbance. Therefore, no pre-knowledge of the ripple needs to be measured. The disturbance produced by the demagnetization and inter-turn faults can be online observed and canceled.
- RO is structurally the same as a high-dimension disturbance observer [12], therefore, it can be designed

following the well-known separation principle. That is, the RO can be added to an existing control loop without affecting the system stability.

- Since torque disturbance is often present even for a healthy motor due to harmonics in the inverter supply, cogging effect, non-sinusoidal flux distribution, current sensor offsets/scaling errors and mechanical misalignments, the RO can be used also in the healthy condition, and once the damage has occurred, the RO can adapt itself and maintains the high performance. Hence, the fault-tolerance capability and robustness of the PMSM can be enhanced.

RO is first proposed in [9], where it is shown that the performance of RO is comparable with RC for torque ripple reduction. However, [9] has not shown RO's potential in the field of fault tolerant control and acoustic noise reduction. The fault tolerant control methods proposed in [13, 14] confirm the feasibility of using compensation current to reduce torque ripple with demagnetization and inter-turn short-circuit respectively. When compared with the methods proposed in [13, 14], the main differences are that 1) No electrical or fault parameters are required using RO. Instead, the mechanical parameters are required; 2) RO not just focuses on one type of fault, but any type of faults that eventually produces torque ripple; 3) Apart from the electrical faults, the acoustic noise due to mechanical faults is also reduced with RO, which is rarely discussed in literature. Besides, the well-known methods of motor current signature analysis for fault detection and signaling are rendered redundant using RO as it self-learns from the disturbances and compensates them. This reduces the computational burden associated with signature analyses that often involve Fourier transformation related calculations [15].

Section II below will review the similarity between RC and RO and provide the design steps for RO. Section III will review the issues in practical implementation of RO. Section IV will show the experimental test results. The back-emf waveforms of

the damaged motor and its healthy version are compared in *Test 1*. Significant reductions in speed ripple and acoustic noise with RO are achieved in *Test 2* with no extra currents and loss for compensation. For *Tests 3-5*, the unbalanced back-emf has been reproduced on the healthy motor by injecting second harmonics in the dq -axis magnetic flux linkage. Moreover, the mechanical fault is reproduced using the healthy motor by mounting the damaged end bearing and break part on the healthy motor. The results show that RO is effective under the whole speed range. High performance is maintained even when such fault is suddenly activated.

II. DESIGN OF THE RO

A. Review the Similarities between RC and RO

Block diagram of a conventional RC with additional correction term can be seen from Fig. 1a where, L_{rc} is the gain of RC, z^{-N} is the delay chain in RC, N is the ratio between the sampling frequency and the target ripple frequency, $G_f(z)$ is known as the stability filter for canceling the delays produced by the plant and any measurement delay, which can be chosen as, for example, the reverse of the plant. $Q_f(z)$ is namely the robustness filter for attenuating the high frequency noise, of which the simplest choice is a forgetting factor (i.e. a constant value from zero to one).

Considering the state-space equation, the mechanical plant of PMSM with periodic disturbance is as given in (1) and Fig. 1b. The inner current loop is ignored in the diagram because it is not the focus of this paper. Also, it is negligible since its dynamics is much faster than the mechanical system.

$$\begin{bmatrix} w_m(k+1) \\ T_e(k+1) \\ x_d(k+1) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13}C_d \\ 0 & 0 & 0 \\ \mathbf{0} & \mathbf{0} & A_d \end{bmatrix} \begin{bmatrix} w_m(k) \\ T_e(k) \\ x_d(k) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ \mathbf{0} \end{bmatrix} T_e^{ref}(k) \quad (1)$$

Where, the periodic disturbance can be expressed using a N -

Fig.1 The similarity between conventional RC and RO

dimension state vector $\mathbf{x}_d$ as in (2) and Fig. 1b.

$$\begin{cases} \mathbf{x}_d(k+1) = \mathbf{A}_d \mathbf{x}_d(k) \\ D(k) = \mathbf{C}_d \mathbf{x}_d(k) \end{cases}, \text{ and } \mathbf{x}_d(k) = \begin{bmatrix} x_{d1}(k) \\ x_{d2}(k) \\ \vdots \\ x_{dN-1}(k) \\ x_{dN}(k) \end{bmatrix}, \mathbf{A}_d = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & 1 \\ 1 & 0 & 0 & \dots & 0 & 0 \end{bmatrix}, \mathbf{C}_d = [1 \ 0 \ 0 \ \dots \ 0 \ 0] \quad (2)$$

According to the concept of disturbance observer, RO observes the disturbance state vector $\mathbf{x}_d$ as in Fig. 1c. It can be seen from Fig. 1c that the left part of RO is equivalent to the reverse of the plant, and therefore equivalent to $G_f(z)$. Whereas, the forgetting factor Q is included in $\bar{\mathbf{A}}_d$ as in (3), and $\mathbf{L} = [0 \ 0 \ 0 \ \dots \ L_{rc}]^T$ is the observer gain.

$$\bar{\mathbf{A}}_d = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & 1 \\ Q & 0 & 0 & \dots & 0 & 0 \end{bmatrix} \quad (3)$$

Overall, the RO in Fig. 1c is equivalent to the RC with a correction term in Fig. 1a. With the correction term, it can be seen in Fig. 1c that the RO will reach steady state once the observed $\hat{x}_{d1}(k)$ matches the real $x_{d1}(k)$ which is indirectly measured from the feedback speed ω_m and previous reference torque T_e^{ref} . While, without the correction term, the RC can only reach steady state when the input error is reduced to zero. Hence, RO can run on its own even without connecting its output to the system, while the RC has to work in the system. This matches the claim that the RO is more independent than the RC. The simulation and experimental results for RO running on its own can be found in [12].

The proposed speed loop control diagram for the damaged motor is drawn as in Fig. 2.

Fig.2 Block diagram of the proposed speed loop for the damaged PMSM

B. Design of PI and RO

It has been mathematically proven in [12] that RO can be designed independently from the speed loop proportional-integral (PI) controller.

Hence, the first step of tuning is to design the PI controller without considering the RO. Through the well-known pole placement method, the PI controller has been designed to obtain 450 Hz speed loop bandwidth in this paper.

The second step is to calculate the length N of the RO memory. It will be mentioned later in Section III that the RO used for this paper is implemented in the rotor angle-domain. And the length N is chosen to be 200. Increasing N can improve the learning accuracy of RO, but $N=200$ is already enough to achieve good results [9, 16].

The third step is to tune Q and L_{rc} . It has been derived in [12] that for stability reasons, the choice of Q and L_{rc} need to satisfy the following condition:

$$|Q - b_1 L_{rc}| < 1, \text{ for } b_1 = \frac{1 - e^{-\frac{B}{J} T_s}}{B}$$

Where, J , B and T_s are the moment of inertia, friction factor and the sampling period, respectively. For the best performance, it is recommended by [12] to set $Q=1$ and L_{rc} to a small value to reduce the interaction between the PI regulator and RO. So, the gain of RO L_{rc} is set to $0.05/b_1$ in this paper.

III. ISSUES IN PRACTICAL IMPLEMENTATION

For practical implementation, the following issues have been considered, which are not shown in the control diagram. These issues have been discussed in [9]. Briefly:

- 1) *The acquisition of speed ω_m* : The position is measured from a 17-bit encoder. The mechanical speed is calculated from the measured position. A low-pass Finite Impulse Response (FIR) filter is used in the speed calculation to remove the quantization error in the position.
- 2) *Adapting the RO to variable speed*: Following the concept of angle-based RC proposed in [16], the RO is implemented with respect to the rotor position in [9] since the disturbance torque is rotor-position-based.
- 3) *The robustness of the RO to speed and load transients*: Results in [9] have confirmed that the speed loop PI is responsible for the transient response, and the observer will not disturb the PI controller.
- 4) *The robustness of the RO against mechanical parameter variations*: Analysis in [9] shows that the performance of RO will degrade if the mechanical parameters are larger than the real parameters. However, the detuned mechanical parameters will not cause any instability. In this paper, the mechanical parameters are set according to the datasheet.
- 5) *The imperfections in current loop due to inverter non-linearity*: Deadbeat current controller [17] is used in this project and the inverter non-linearity is not compensated because the RO will compensate the error.

IV. EXPERIMENTAL TEST RESULTS

Experimental rig as in Fig. 3 has been set-up. The damaged motor has been opened, where clear burn marks can be seen on the stator. It is also identified that the acoustic noise is generated by the end bearing with break part in Fig. 3. The machine and

control parameters are shown in Table I. The control algorithms are implemented on a high performance FPGA/DSP platform [18]. The length of the damaged motor is larger than the healthy motor because the damaged motor is equipped with an electrical holding brake (common in industrial servomotors). The Smart Sensor (AR854) sound meter has been used for the tests, of which the measurement range is 20 Hz $\sim$ 8 kHz and the accuracy is ± 1.5 dB.

In the *Test 1* below, the back-emf of the broken motor will be plotted. As shown in Fig. 4b, the back-emf has become unbalanced after the damage. The dq -axis components of the magnetic flux linkage for the damaged motor have been calculated. The results in *Test 2* compare the speed ripple and audible noise with/without RO using both the damaged motor and the healthy motor.

Test 1 and *2* have been carried out in authors' previous work in [19]. All the following results are exclusively presented in this paper. More results from *Test 2* including the torque, dq -axis currents, current loss are added in Fig. 5. From *Test 3*, the damage condition is reproduced using the healthy motor. The dq -axis magnetic flux linkages calculated from *Test 1* is used to reproduce the unbalanced back-emf in the deadbeat controller (see section C for details). The acoustic noise is reproduced by reusing the damaged end bearing part on the healthy motor. In this way, we can activate and deactivate the damage freely and verify if high performance can be maintained when the motor is suddenly damaged. The motor with reproduced fault will be referred as the "unhealthy motor" in the rest of the paper.

In *Test 3*, the speed ripple and acoustic noise at different speed at steady state have been measured for the following four

conditions:

- 1) The healthy motor without RO (HM).
- 2) The healthy motor with RO (HMRO).
- 3) The unhealthy motor with unbalanced back-emf activated, and without RO (UHM).
- 4) The unhealthy motor with unbalanced back-emf activated, and with RO (UHMRO).

In *Test 4*, the speed and noise during step transients for the above four conditions are measured.

In *Test 5*, the speed and noise when the fault is suddenly activated are acquired to verify that the high performance is maintained when the fault happens.

A. Test 1: Back-emf test

To analyse the damage, a load motor has been used to drive the damaged motor at constant speed, the back-emf waveforms are recorded and compared with the healthy motor. The line-to-line voltages at 125 rad/s are shown in Fig. 4a. The voltages are converted into the phase voltages in alpha-beta frame and plotted in Fig. 4b. Results show that the back-emf of the damaged motor is unbalanced and has shrunk. Consequently, second order components are produced in the dq -axis magnetic flux as shown in (4), where, θ_e is the electrical angular position. For the healthy motor, the magnetic flux linkage ψ_m in Table I only has the d -axis component.

Fig.3 Test rig

TABLE I
HEALTHY MACHINE AND CONTROL PARAMETERS

Parameter	Value [Unit]	Parameter	Value [Unit]
Number of pole pairs	4	dq -axis inductances L_{dq}	2.6 [mH]
Stator resistance R_s	0.43 [Ohms]	Magnetic flux linkage ψ_m	0.0589 [Wb]
Friction factor B	$0.8e^{-3}$ [Nms/rad]	Moment of inertia J	$1.06e^{-4}$ [kgm ²]
Forgetting factor Q	1	Observer gain matrix L	$[0 \ 0 \ \dots \ 0 \ 0.0532]^T$
Sampling period T_s	0.0001 [s]	Length of memory N	200

(a) Line-to-line voltage when driven from load side

(b) Back-emf in alpha-beta frame

Fig.4 Back-emf at 125 rad/s.

$$\begin{cases} \psi_{md} = \psi_m - 0.00338 \cos(2\theta_e) \\ \psi_{mq} = 0.00338 \sin(2\theta_e) \end{cases} \quad (4)$$

Therefore, the updated dq -axis voltage equations including the unbalanced back-emf are as (5).

$$\begin{cases} u_d = R_s i_d + \frac{d(L_d i_d + \psi_{md})}{dt} - \omega_e (L_q i_q + \psi_{mq}) \\ u_q = R_s i_q + \frac{d(L_q i_q + \psi_{mq})}{dt} + \omega_e (L_d i_d + \psi_{md}) \end{cases} \quad (5)$$

Where, u_{dq} is dq -axis voltage, i_{dq} is dq -axis current, ω_e is the electrical angular speed, R_s , L_d , L_q are defined as in Table I.

B. Test 2: Effect of the Damage

The speed waveforms and their Fast Fourier Transform (FFT) results of the damaged motor (DM) and the healthy motor (HM) are shown in Fig. 5a and Fig. 5b. Where, the speed ripple has been reduced significantly from $-11.4 \sim +15.5$ rpm to $-1.7 \sim +1.5$ rpm. The reduction in speed ripple is the result of the reduction of torque ripple. As plotted in Fig. 5c, the net torque T_{net} calculated from (6) has its peak to peak ripple reduced from 0.13 Nm to 0.011 Nm for the damaged motor, the reduction of which is 91.5%. Also, for the healthy motor, the torque ripple is reduced by 54%.

$$T_{net}(k) = J \frac{\omega_m(k+20) - \omega_m(k)}{20T_s} + B\omega_m(k) \quad (6)$$

In (6), parameters J , B and T_s are given in Table I. To reduce the quantization noise in the speed feedback ω_m , it has been down-sampled by 20 for the torque calculation.

To analyze the current loss, the dq -axis current i_{dq} and the current loss P_j calculated from (7) are plotted in Fig. 5d and Fig. 5e, respectively. The electrical resistance R_s in (7) is as in Table I.

$$P_j(k) = 1.5R_s \sqrt{i_d^2(k) + i_q^2(k)} \quad (7)$$

Impressively, adding RO does not increase the current loss at all. Instead, the peak value of the current loss is smaller with RO. However, due to the damage, the motor does need to draw a significant amount of additional currents to generate the same average torque.

This characteristic of RO makes it especially useful for mission-critical applications where motor needs to finish the rest of the task even after a damage has happened. Without adding any redundancy, only by adding the RO in control, it can help the motor maintaining its good performance.

The waterfall plots in Fig. 6 also show that the acoustic noise of the damaged motor is 9.2 dB lower after applying RO and becomes comparable with the healthy motor.

C. Test 3: Performance at Steady State

To reproduce the unbalanced back-emf, equation (5) has been used in the deadbeat current controller. In details, the deadbeat current controller used in this paper consists of two steps including current prediction, and reference voltage calculation. For example, during the k^{th} sampling interval, the dq -axis current at the beginning of the $(k+1)^{\text{th}}$ interval can be

Fig.5 Speed, torque, dq -axis currents and current loss the damaged and healthy motor at speed at 500 rpm with/without RO.

Fig.6 Acoustic noise of the damaged at speed at 500 rpm with/without RO for compensation.

predicted as in (8) assuming the motor is healthy.

$$\begin{cases} i_d^{pre}(k+1) = (1 - \frac{R_s T_s}{L_d}) i_d(k) + \frac{L_q T_s}{L_d} \omega_e(k) i_q(k) + \frac{T_s}{L_d} u_d^{ref}(k) \\ i_q^{pre}(k+1) = (1 - \frac{R_s T_s}{L_q}) i_q(k) - \frac{L_d T_s}{L_q} \omega_e(k) i_d(k) + \frac{T_s}{L_q} u_q^{ref}(k) - \frac{\psi_m T_s}{L_q} \omega_e(k) \end{cases} \quad (8)$$

Where, $u_{dq}^{ref}(k)$ is the reference dq -axis voltage calculated in the previous interval.

Based on the assumption that the reference current can be reached in one “beat” (i.e. after one sampling period T_s at t_{k+2}), the voltage reference to be applied at t_{k+1} can be calculated as in (9).

$$\begin{cases} u_d^{ref}(k+1) = R_s i_d^{pre}(k+1) + L_d \frac{i_d^{ref} - i_d^{pre}(k+1)}{T_s} - \omega_e(k) [L_q i_q^{pre}(k+1) + \psi_{mq}(k)] \\ u_q^{ref}(k+1) = R_s i_q^{pre}(k+1) + L_q \frac{i_q^{ref} - i_q^{pre}(k+1)}{T_s} + \omega_e(k) [L_d i_d^{pre}(k+1) + \psi_{md}(k)] \end{cases} \quad (9)$$

Where, the magnetic flux linkage $\psi_{md}(k)$ and $\psi_{mq}(k)$ are calculated from (4). By applying (9) for calculating the voltage reference, the fault is activated. To disable the fault, set $\psi_{md} = \psi_m$ and $\psi_{mq} = 0$.

This method does not simulate exactly the increased current due to the damage, but for speed loop, it simulates well the influence of the damage on speed ripple. Fig. 7a compares the FFT of the speed at 500 rpm when using the original damaged

Fig.7 Performance at steady state: (a) FFT of speed at 500 rpm for the original damaged motor and the unhealthy motor with reproduced unbalanced back-emf. (b) Speed ripple at 500 rpm. (c) Speed ripple with/without RO. (d) Acoustic noise with/without RO.

Fig.8 Speed ripple at speed transient from 500 rpm to 1500 rpm with/without RO.

motor and when using the unhealthy motor with added unbalanced back-emf. Results prove that the similar speed ripple is reproduced.

At 500 rpm, Fig. 7b compares the effectiveness of the RO on the faulty motor with reproduced fault and on the healthy motor. It confirms again the conclusions in *Test 2* that with RO the performance of the unhealthy motor is even better than the healthy motor without RO.

Repeating the test at 200~3000 rpm, Fig. 7c shows that significant reduction of speed ripple has been achieved. Consequently, as plotted in Fig. 7d, the acoustic noise of the unhealthy motor under this speed range has been suppressed successfully with RO.

D. Test 4: Performance at Speed Transient

When a step in the speed reference is applied, the speed ripple of the unhealthy motor can continuously be reduced as shown in Fig. 8. Correspondingly, the waterfall plots in Fig. 9 confirm that the acoustic noise of the unhealthy motor is significantly reduced with RO. The noise readings in dB measured by a sound meter at steady state are noted in each plot in Fig. 9.

E. Test 5: Performance when Suddenly Damaged

So far, the results can prove that after the damage has happened, the proposed RO can maintain the speed control performance and maintain the audible noise level at constant speed and during speed transients. The next question would be how the performance of RO is at the very moment when the

Fig.9 Waterfall plot of acoustic noise at speed transient from 500 rpm to 1500 rpm with/without RO.

damage suddenly occurs.

Fig. 10 and Fig. 11 capture the speed and noise before and after the unbalanced back-emf is activated. As shown, the speed ripple and noise have been well-maintained after the unbalanced back-emf has been applied.

The sudden damage can be modelled as an additional

periodic disturbance torque added to the original disturbance D in Fig. 2. It can be known from Section II-B that the stability of RO is not affected by the profile shape of the disturbance. Since the disturbance is still periodic with respect to the mechanical position as assumed, the RO learns the updated profile and improves the performance cycle by cycle. This explains why the RO remains stable in Fig. 10.

V. CONCLUSION

The aim of this paper is to evaluate the effectiveness of the RO on smoothing the exceedingly large speed ripple and reducing the intolerable acoustic noise of a motor damaged by overcurrent. Experimental tests have shown that significant speed ripple and noise reductions are achieved.

Following our previous work in [19], the extra results shown in *Test 2-5* confirm that RO is able to smooth the speed and reduce the acoustic noise under full range of speed at steady state, during speed transients and even during a sudden damage. And the compensation action generated RO does not increase the overall current. Instead, using RO can improve the current ripple so as the current loss.

This novel work is important because it opens the possibility of reusing the damaged motor and still achieve high performance such as in servo applications or mission-critical applications. For healthy motor, the technology can also help enhancing the fault-tolerance capability of the PMSM by continuous learning about the speed ripple arising from sudden faults and compensating it as in *Test 5*.

The authors believe that this work transcends the state-of-the-art of PM servomotors' diagnostics and reuse, and opens new avenues for research in this direction.

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Fig.10 Speed at 1000 rpm with/without RO before and after the fault happens.

Fig.11 Waterfall plot of acoustic noise at 1000 rpm with/without RO before and after the fault happens.

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