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

Mi Tang, Member, IEEE, Shafiq Odhano, Senior Member, IEEE, Andrea Formentini, Member, IEEE, and Pericle Zanchetta, Fellow, IEEE

Abstract—A lab-used servo permanent magnet synchronous motor has been accidentally damaged due to overcurrent. On the 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 electromotive force 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 article aims to reuse this damaged motor by adding a repetitive observer (RO) to the existing speed loop, hence 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 of the feedback loop, while the stability of the 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, demagnetization, fault tolerant, repetitive observer (RO), torque ripple reduction.

I. INTRODUCTION

A PERMANENT magnet synchronous motor (PMSM) is preferred over the induction motor due to its high efficiency. On the one hand, the use of permanent magnet results in the high-power density; on the other hand, the permanent magnet material may suffer from the demagnetization as the operating temperature increases. The rise in temperature also brings risks for insulation failures that may lead to interturn short circuits or more severe short circuits between the phases and phase-to-ground. According to the article presented in [1] and [2], 38% of all motor faults are stator faults, and the interturn faults are most likely to happen. If either the demagnetization or interturn fault happens, harmonics in the dq-axis flux linkage will occur. Such harmonics will eventually produce torque ripple. Besides the electrical faults, mechanical faults, such as bearing faults, share 40%–50% of all motor faults [3]. Both the electrical and mechanical faults can produce acoustic noise. On the 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]. Zhu et al. [5] proposed a method to detect demagnetization by acoustic noise. The vibration is used in [6] to monitor the partial demagnetization and interturn short-circuit faults.

A lab-used PMSM for servo application has been damaged accidentally due to overcurrent. As a result, its back electromotive force (EMF) has become unbalanced, and due to the mechanical damage, in its end, bearing and break part, 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 (DM) is normally replaced and disposed. It is barely discussed in the existing literature that the DM can be reused with proper compensations without introducing redundancy [7], [8]. Hence, the aim of this article is to reuse this motor by applying the recently developed repetitive observer (RO) [9] to smooth the speed and reduce the acoustic noise. RO is considered suitable for this application because of the following benefits.

1) 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 preknowledge of the ripple needs to be measured. The disturbance produced by the demagnetization and interturn faults can be observed online and canceled.

2) RO is structurally the same as a high-dimensional 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.

3) Since torque disturbance is often present even for a healthy motor (HM) due to harmonics in the inverter supply, cogging effect, nonsinusoidal flux distribution, current sensor offsets/scaling errors, and mechanical misalignments, the RO can also be used 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, Tang et al. [9] have not shown RO’s potential in the field of fault-tolerant control and acoustic noise reduction. The fault-tolerant control methods proposed in [13] and [14] confirm the feasibility of using compensation current to reduce the torque ripple with demagnetization and interturn short circuit, respectively. When compared with the methods proposed in [13] and [14], the main differences are as follows.

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 the literature.

Besides, the well-known methods of motor current signature analysis for fault detection and signaling are rendered redundant using the RO as it self-learns from the disturbances and compensates them. This reduces the computational burden associated with the signature analyses that often involve Fourier transformation-related calculations [15].

Section II will review the similarity between the RC and RO and provide the design steps for RO. Section III will review the issues in the practical implementation of RO. Section IV will show the experimental test results. The back EMF waveforms of the DM 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 HM by injecting second harmonics in the dq-axis magnetic flux linkage. Moreover, the mechanical fault is reproduced using the HM by mounting the damaged end bearing and break part on the HM. The results show that RO is effective under the whole speed range. High performance is maintained even when such a fault is suddenly activated.

II. DESIGN OF THE RO

A. Review the Similarities Between the RC and RO

The block diagram of a conventional RC with an additional correction term can be seen from Fig. 1(a), where \( L_{rc} \) is the gain of RC, \( x^N \) is the delay chain in RC, \( N \) is the ratio between the sampling frequency and the target ripple frequency, and \( G_f(z) \) 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 given in (1) and Fig. 1(b). The inner current loop is ignored in the diagram because it is not the focus of this article. Also, it is negligible since its dynamics is much faster than the mechanical system.

\[
\begin{align*}
\begin{bmatrix}
    w_m (k + 1) \\
    T_e (k + 1) \\
    x_d (k + 1)
\end{bmatrix}
&= \begin{bmatrix}
    a_{11} & a_{12} & a_{13}C_d \\
    0 & 0 & 0 \\
    0 & 0 & A_d
\end{bmatrix}
\begin{bmatrix}
    w_m (k) \\
    T_e (k) \\
    x_d (k)
\end{bmatrix}
+ \begin{bmatrix}
    0 \\
    1 \\
    0
\end{bmatrix} T_e^{ref} (k)
\end{align*}
\]

(1)

where the periodic disturbance can be expressed using an \( N \)-dimensional state vector \( x_d \) in (2) and Fig. 1(b).

\[
\begin{align*}
\begin{bmatrix}
    x_{di1} (k) \\
    x_{di2} (k) \\
    \cdots \\
    x_{diN} (k)
\end{bmatrix}
&= \begin{bmatrix}
    0 & 1 & 0 & \ldots & 0 & 0 \\
    0 & 0 & 1 & \ldots & 0 & 0 \\
    \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
    0 & 0 & 0 & \ldots & 0 & 1 \\
    1 & 0 & 0 & \ldots & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    x_{di0} (k) \\
    x_{di1} (k) \\
    \cdots \\
    x_{diN-1} (k) \\
    x_{diN} (k)
\end{bmatrix}
\end{align*}
\]

(2)

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

\[
\begin{bmatrix}
    0 & 1 & 0 & \ldots & 0 & 0 \\
    0 & 0 & 1 & \ldots & 0 & 0 \\
    \ldots & \ldots & \ldots & \ldots & \ldots & \ldots \\
    0 & 0 & 0 & \ldots & 0 & 1 \\
    Q & 0 & 0 & \ldots & 0 & 0
\end{bmatrix}
\]

(3)

Overall, the RO in Fig. 1(c) is equivalent to the RC with a correction term in Fig. 1(a). With the correction term, it can be seen in Fig. 1(c) that the RO will reach the steady state once the observed \( \hat{x}_{di1} (k) \) matches the real \( x_{di1} (k) \), which is indirectly measured from the feedback speed \( \omega_m \) and the previous reference torque \( T_{e}^{ref} \). However, without the correction term, the RC can only reach the steady state when the input error is reduced to zero. Hence, RO can run on its own even without connecting...
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 DM is drawn in Fig. 2.

### B. Design of Proportional–Integral (PI) and RO

It has been mathematically proven in [12] that the RO can be designed independently from the speed loop 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 article.

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 article 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 $L_{rc}$ needs to satisfy the following condition:

$$|Q - b_1 L_{rc}| < 1,$$

for $b_1 = 1 - e^{-\frac{J}{B T_s}}$, where $J$, $B$, and $T_s$ are the moment of inertia, friction factor, and sampling period, respectively. For the best performance, it is recommended by Tang and Zanchetta [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 article.

### 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] as follows.

1) The acquisition of speed $\omega_m$: The position is measured from a 17-bit encoder. The mechanical speed is calculated from the measured position. A low-pass finite impulse response 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: The results in [9] have confirmed that the speed loop PI controller has good performance.
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 \( \psi_m \) | 0.0589 [Wb] |
| Friction factor \( B \) | \( 0.8 \text{e}^3 \) [Nms/rad] | Moment of inertia \( J \) | 1.06\text{e}^4 [kgm^2] |
| Forgetting factor \( Q \) | 1            | Observer gain matrix \( L \) | \([0 \ 0 \ ... \ 0\)
| Sampling period \( T_s \) | 0.0001 [s]  | Length of memory \( N \) | 200          |

is responsible for the transient response, and the observer will not disturb the PI controller.

4) The robustness of the RO against the mechanical parameter variations: The 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 article, the mechanical parameters are set according to the datasheet.

5) The imperfections in the current loop due to inverter nonlinearity: A deadbeat current controller [17] is used in this project and the inverter nonlinearity is not compensated because the RO will compensate the error.

IV. EXPERIMENTAL TEST RESULTS

The experimental rig, as shown in Fig. 3, has been set up. The DM 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 the break part in Fig. 3. The machine and control parameters are given in Table I. The control algorithms are implemented on a high-performance FPGA/DSP platform [18]. The length of the DM is larger than the HM because the DM is equipped with an electrical holding brake (common in industrial servomotors). The smart sensor (AR854) sound meter has been used for the tests in which the measurement range is 20 Hz–8 kHz and the accuracy is \( \pm 1.5 \text{ dB} \).

Latter in Test 1, the back EMF of the broken motor will be plotted. As shown in Fig. 4(b), the back EMF has become unbalanced after the damage. The \( dq \)-axis components of the magnetic flux linkage for the DM have been calculated. The results in Test 2 compare the speed ripple and audible noise with/without RO using both the DM and the HM.

Tests 1 and 2 have been carried out in the authors’ previous work in [19]. All the following results are exclusively presented in this article. More results from Test 2, including the torque, \( dq \)-axis currents, and current loss, are added in Fig. 5. From Test 3, the damage condition is reproduced using the HM. The \( dq \)-axis magnetic flux linkages calculated from Test 1 are used to reproduce the unbalanced back EMF in the deadbeat controller (see Section IV-C for detail). The acoustic noise is reproduced by reusing the damaged end bearing part on the HM. 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 a reproduced fault will be referred as the “unhealthy motor” in the rest of the article.
In Test 3, the speed ripple and acoustic noise at different speeds at steady state have been measured for the following four conditions:
1) the HM without RO (HM);
2) the HM 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 analyze the damage, a load motor has been used to drive the DM at a constant speed; the back EMF waveforms are recorded and compared with the HM. The line-to-line voltages at 125 rad/s are shown in Fig. 4(a). The voltages are converted into the phase voltages in the alpha–beta frame and plotted in Fig. 4(b). The results show that the back EMF of the DM is unbalanced and has shrunk. Consequently, second-order components are produced in the dq-axis magnetic flux, as shown in (4), where $\theta_e$ is the electrical angular position. For the HM, the magnetic flux linkage $\psi_m$ in Table I has only the d-axis component.

\[
\begin{align*}
\psi_{md} &= \psi_m - 0.00338 \cos(2\theta_e) \\
\psi_{mq} &= 0.00338 \sin(2\theta_e)
\end{align*}
\]  

Therefore, the updated dq-axis voltage equations, including the unbalanced back EMF, are as follows:

\[
\begin{align*}
u_d &= R_s i_d + \frac{d(L_di_d + \psi_{md})}{dt} - \omega_e (L_q i_q + \psi_{mq}) \\
u_q &= R_s i_q + \frac{d(L_q i_q + \psi_{mq})}{dt} + \omega_e (L_d i_d + \psi_{md})
\end{align*}
\]  

where $u_{dq}$ is the dq-axis voltage, $i_{dq}$ is the dq-axis current, $\omega_e$ is the electrical angular speed, and $R_s$, $L_d$, and $L_q$ are defined in Table I.

B. Test 2: Effect of the Damage

The speed waveforms and their fast Fourier transform (FFT) results of the DM and HM are shown in Fig. 5(a) and (b), where...
the speed ripple has been reduced significantly from $-11.4 \sim +15.5$ to $-1.7 \sim +1.5$ r/min. The reduction in speed ripple is the result of the reduction in torque ripple. As plotted in Fig. 5(c), the net torque $T_{\text{net}}$ calculated from (6) has its peak-to-peak ripple reduced from 0.13 to 0.011 N·m for the DM, the reduction of which is 91.5%. Also, for the HM, the torque ripple is reduced by 54%.

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

In (6), parameters $J$, $B$, and $T_s$ are given in Table I. To reduce the quantization noise in the speed feedback $\omega_m$, it has been downsampled 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. 5(d) and 5(e), respectively. The electrical resistance $R_s$ in (7) is given in Table I.

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

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 the motor needs to finish the rest of the task even after the 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 DM is 9.2 dB lower after applying the RO and becomes comparable with the HM.

C. Test 3: Performance at Steady State

To reproduce the unbalanced back EMF, (5) has been used in the deadbeat current controller. In detail, the deadbeat current controller used in this article 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 $(k+1)$th interval can be predicted in (8), assuming the motor is healthy

$$
\begin{align*}
\dot{i}_d^{\text{pre}}(k+1) &= \left(1 - \frac{R_s T_s}{L_d}\right) i_d(k) + \frac{L_d T_s}{L_d} \omega_e(k) i_q(k) \\
&+ \frac{T_s}{L_d} u_{d}^{\text{ref}}(k)\\
\dot{i}_q^{\text{pre}}(k+1) &= \left(1 - \frac{R_s T_s}{L_q}\right) i_q(k) - \frac{L_d T_s}{L_q} \omega_e(k) i_d(k) \\
&+ \frac{T_s}{L_q} u_{q}^{\text{ref}}(k) - \frac{\omega_e T_s}{L_q} \omega_e(k)
\end{align*}
$$

(8)

where $u_{d}^{\text{ref}}(k)$ 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 $k+2$), the voltage reference to be applied at $t_{k+1}$ can be calculated as follows:

$$
\begin{align*}
u_{d}^{\text{ref}}(k+1) &= R_s i_{d}^{\text{pre}}(k+1) + L_d \frac{\dot{i}_d^{\text{pre}}(k+1)}{T_s} - \omega_e(k) L_q i_{q}^{\text{pre}}(k+1) + \psi_{mq}(k) \\
u_{q}^{\text{ref}}(k+1) &= R_s i_{q}^{\text{pre}}(k+1) + L_q \frac{\dot{i}_q^{\text{pre}}(k+1)}{T_s} + \omega_e(k) L_d i_{d}^{\text{pre}}(k+1) + \psi_{md}(k)
\end{align*}
$$

(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 $\psi_{md} = \psi_{mq} = 0$.

This method does not simulate exactly the increased current due to the damage, but for the speed loop, it simulates well the influence of the damage on the speed ripple. Fig. 7(a) compares the FFT of the speed at 500 r/min when using the original DM and when using the unhealthy motor with added unbalanced back EMF. The results prove that a similar speed ripple is reproduced.

At 500 r/min, Fig. 7(b) compares the effectiveness of the RO on the faulty motor with the reproduced fault on the HM. It confirms the conclusions again in Test 2 that with RO the performance of the unhealthy motor is even better than the HM without RO.

Repeating the test at 200–3000 r/min, Fig. 7(c) shows that the significant reduction of the speed ripple has been achieved. Consequently, as plotted in Fig. 7(d), 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 decibel measured by a sound meter at the 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 a constant speed and during speed transients. The next question would be how the performance of RO is at the very moment when the damage suddenly occurs.

Figs. 10 and 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 modeled 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 article 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. The experimental tests have shown that significant speed ripple and noise reductions are achieved.

Following our previous work in [19], the extra results, as shown in Test 2–5, confirm that RO is able to smooth the speed and reduce the acoustic noise under a full range of speed at the 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 DM and still achieves high performance, such as in servo applications or mission-critical applications. For HM, the technology can also help to enhance the fault tolerance capability of the PMSM by continuous learning about the speed ripple arising from the 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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Mi Tang (Member, IEEE) was born in Chengdu, Sichuan, China, in 1990. She received the M.Sc. degree in electrical engineering and the Ph.D. degree in electrical and electronic engineering from the University of Nottingham, Nottingham, U.K., in 2012 and 2017, respectively. She is currently a Research Fellow with the Power Electronics and Machine Control Group, University of Nottingham, Nottingham, U.K. Her research interests include deadbeat control and repetitive control.

Shafiq Odhano (Senior Member, IEEE) received the M.Sc. degree in electrical engineering and the Ph.D. degree in power electronics, machines, and drives from the Politecnico di Torino, Turin, Italy, in 2014. He has been affiliated as a Postdoctoral Research Fellow with the Politecnico di Torino and a Research Fellow with the University of Nottingham, Nottingham, U.K. He is currently a Lecturer in Electric Drives with Newcastle University, Newcastle Upon Tyne, U.K. His research interests include high-performance control of servodrives, model predictive control of power converters, and self-commissioning of ac motor drives. Dr. Odhano was a recipient of the IEEE-IAAS Prize Paper Award in 2015.

Andrea Formentini (Member, IEEE) received the M.S. degree in computer engineering and the Ph.D. degree in electrical engineering from the University of Genova, Genova, Italy, in 2010 and 2014, respectively. He was a Research Fellow with the Power Electronics, Machines, and Control Group, University of Nottingham, Nottingham, U.K., where he has been an Assistant Professor of Control of power electronics systems, since 2018. His research interests include control of electrical machine drives, power converters, and microgrids.

Pericle Zanchetta (Fellow, IEEE) received the M.Eng. degree in electronic engineering and the Ph.D. degree in electrical engineering from the Technical University of Bari, Bari, Italy, in 1993 and 1997, respectively. In 1998, he was an Assistant Professor of power electronics with the Technical University of Bari. In 2001, he was a Lecturer in Control of Power Electronics Systems with the Power Electronics, Machine, and Control Research Group, University of Nottingham, Nottingham, U.K., where he is currently a Professor of control of power electronics systems. He has authored or coauthored more than 330 peer-reviewed papers. His research interests include control and optimization of power converters and drives, matrix, and multilevel converters. Dr. Zanchetta has been the Chair of the IEEE-IAAS Industrial Power Converter Committee (IPCC) and is currently the Transactions Review Chair for IPCC. He is also the Vice-Chair of the Department of IEEE-IAAS Industrial Power Conversion Systems.