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Off-Line Detection of Static Eccentricity in Salient-Pole Synchronous Machines

K. N. Gyftakis, C. A. Platero and S. Bernal

Abstract – **Since synchronous generators are the main electric power producing devices, it is crucial to guarantee their safe and reliable operation. However, faults may appear and inflict great losses. So, condition monitoring of such machines is critical to avoid unscheduled stops and unplanned maintenance. This paper works towards that direction. The authors are proposing a new off-line method to reliably detect the static eccentricity fault in synchronous salient pole electrical machines. The method is based on the monitoring of all three phase currents of the machine during locked rotor at three different rotor positions. A pseudo zero-sequence current is then calculated, the frequency spectrum of which can reveal reliable indicators to detect this fault. The proposed method has been tested experimentally with success, while the results indicate that it is possible to estimate the fault level severity.**

Index Terms—**Condition monitoring, Eccentricity, Fault diagnosis, Salient-pole machines, Synchronous machines.**

I. Introduction

SYNCHRONOUS machines are devices that dominate the field of large electromechanical energy conversion operating as high power generators. Due to their critical role in the modern world, synchronous machines should operate uninterrupted and under reliable condition monitoring strategies. However, faults do appear inflicting severe financial losses due to interruption of the production as well as service and maintenance. The losses are proportional to the machine importance and rating [1].

Salient-pole synchronous generators are mainly used in hydroelectric plants and industrial generators driven by gas or steam turbine. In such applications, the machines must operate continuously for a long time before undergoing inspection and maintenance [2]. There are many different faults that might appear in salient-pole machines, however the major ones are the eccentricity and electrical faults [3]. It is to be noted that overall approximately 60% of faults in electrical machines are of mechanical nature [4].

Eccentricity can be of two types: static and dynamic. Static is when the rotor is displaced in a fixed position and as a consequence the air gap is asymmetrical but does not vary with time. On the other hand, the rotor center is changing position in the case of dynamic eccentricity and as a result the air-gap is varying with time. The combination between the two above cases is called mixed eccentricity. Practically, all electrical machines have a small level of mixed eccentricity which should be below 10% for new ones.

Static eccentricity is a fault strongly related to the manufacturing stages of the machine. It is caused by improper positioning of the rotor in the stator or the ovality of the stator core [5]. Specifically for salient-pole generators, it is impossible to centre the rotor perfectly within the stator during the assembly process due to the very small air-gap to stator bore diameter ratio [6]. Static eccentricity may increase due to the deformation of bearings or stator caused by gravity, especially in large machines.

Several works have focused on the impact of eccentricity on the behaviour of synchronous generators [6]-[9]. If a synchronous machine is operating under eccentric conditions then there is a significant increase in the electromagnetic radial and tangential forces [7]. It was shown [8] that eddy currents are induced in the damping bars even at no-load, due to the variation of the air-gap reluctance in eccentric synchronous generators. A study on the Unbalanced Magnetic Pull (UMP) in eccentric salient-pole generators showed that static and dynamic eccentricities are almost independent [6]. Finally, the effect of the damper winding on the eccentricity forces is small, probably due to the high damper winding resistance [9].

Regarding the diagnosis of the eccentricity fault in synchronous machines the literature is poor compared to the work that has been performed in induction motors. However, some significant past works are referred here. Some works have focused on intrusive methods such as the monitoring of the air-gap radial flux [2], [10]. Alternatively, it has been proposed to monitor the shaft voltage during the generator operation [11]-[12]. However the reliability of this method is questionable. The 5th harmonic of the shaft voltage used as eccentricity signature may increase or decrease depending on the orientation of the eccentricity relative to the key way [11]. In the same work it is reported that manufacturing asymmetries might cause complications and introduce unreliability when using shaft voltages as a diagnostic mean [11]. Furthermore, it has been stated that the measurement noise may influence the results. However in [12] it is shown that the shaft voltages are more responsive to the static eccentricity fault while causing a low identification error. Moreover, the no-load induced stator voltage's spectra [1], [13] and space vector [14] have been used. Additionally, in [1]

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the authors propose the monitoring specific signatures in the rotor current spectrum. In [15] an off-line technique is proposed to detect eccentricity in salient-pole synchronous machines, based on the standard short-circuit test where the higher harmonic index of the line currents is analysed. Finally, an interesting method is presented in [16]-[17] where the Split-Phase Currents analysis is adopted. This method is based on the measurement of currents in the distinct branches of parallel-connected windings.

In this paper, the authors propose a new method to detect the static eccentricity fault and its severity in salient-pole synchronous machines. The work is based on the monitoring of the three phase currents at three different rotor positions and then calculating a pseudo zero-sequence current. A similar technique was used successfully in the past to detect static eccentricity is 3-phase induction motors [18]. However, the application of this older philosophy in salient pole machines met many challenges and issues due to the different rotor geometry, the non-uniform air-gap and the existence of the rotor winding. As a result a new methodology had to be invented to account for all new parameters. It will be shown that the proposed technique can be reliably used for static eccentricity fault detection in salient-pole machines. Moreover, the proposed method could be valuable for hydrogen cooled synchronous generators because in those machines it is difficult to open and use a wedge to measure the air-gap. Finally, it is simple, low cost, off-line and most importantly non-intrusive.

II. Presentation of the Proposed Method

When a salient pole generator suffering from a static eccentricity condition, the rotor centre is displaced from the stator geometrical centre, however remains fixed over time. Static eccentricity makes the machine air gap asymmetrical in space. So, some part of the rotor will be closer to the stator. This displacement leads to reduction of the local reluctance and consequently more flux will flow causing a local saturation effect. The saturation impact due to the static eccentricity is of course maximum when a salient pole of the rotor is across the slots of a stator phase carrying maximum current.

The above described condition is the basis of the proposed method. The three stator phases are connected in Y and fed by the 3-phase power supply. Due to the absence of back EMF and the low stator windings resistance the supply voltage was set to a low value of 24Vac, which is not harmful for the machine, the parameters of which are shown in Table I.

TABLE I
CHARACTERISTICS OF THE SYNCHRONOUS GENERATOR USED IN THE EXPERIMENTAL TESTING

Rated apparent power	5 kVA
Rated voltage (± 5%)	400 V
Frequency	50 Hz
Pole pairs	2
Rated speed	1500 rpm
Rated Power Factor	0.8
Rated Excitation Voltage	22.1 V
Rotor resistance	10.5 Ω

The rotor winding is shorted in order to draw eddy currents induced by the rotating magnetic field of the stator and magnetize the rotor iron core body. The phase currents are monitored using a four channel digital storage oscilloscope and AC/DC current clamps. The oscilloscope has a 100 MHz bandwidth and a 2 GS/s sample rate. The current clamps are based on Hall Effect technology and are suitable for AC and DC current. The accuracy is ± 1% of the reading ±2 mA up to 20 MHz.

The electric diagram of the synchronous machine under the experimental testing is shown in Fig. 1. The method consists of three measurement steps. For the first step, the rotor is externally shifted until the monitored stator current of the first phase gets its maximum rms value. This is an indicator that a salient pole of the rotor, which is taken as reference, is at 90º aligned with the bisector of the slots wounded by the first phase. At this position the rotor is locked and the machine is supplied by the three-phase sinusoidal supply where the current of the first phase is monitored and stored. Since the physical model of the machine is static the captured signal does not need to be long for spectral analysis. In this work, only 5 periods of the first phase current were stored.

The next step is to shift the rotor by 120° electrical degrees so that now the referenced salient pole is aligned at 90º phase difference with the bisector of phase 2 slots. The measurement is repeated and the second current is captured. Finally, the procedure is repeated one more time where the rotor is shifted by 240° and the third phase current is stored. This procedure is illustrated in the following Fig. 2. The three independent phase currents are then added over time resulting in the calculation of a pseudo zero-sequence current.

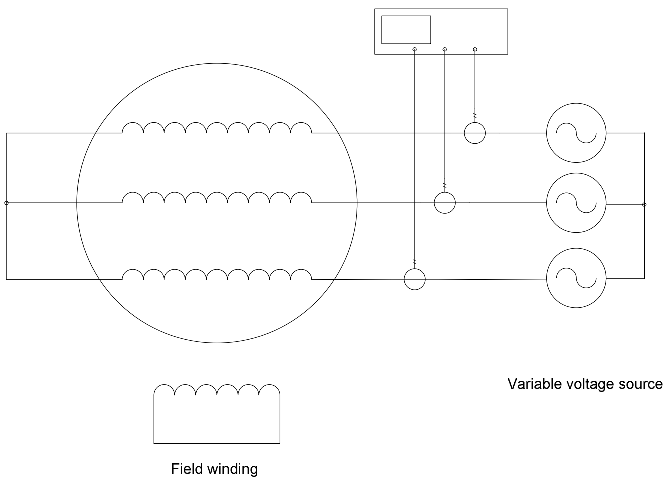
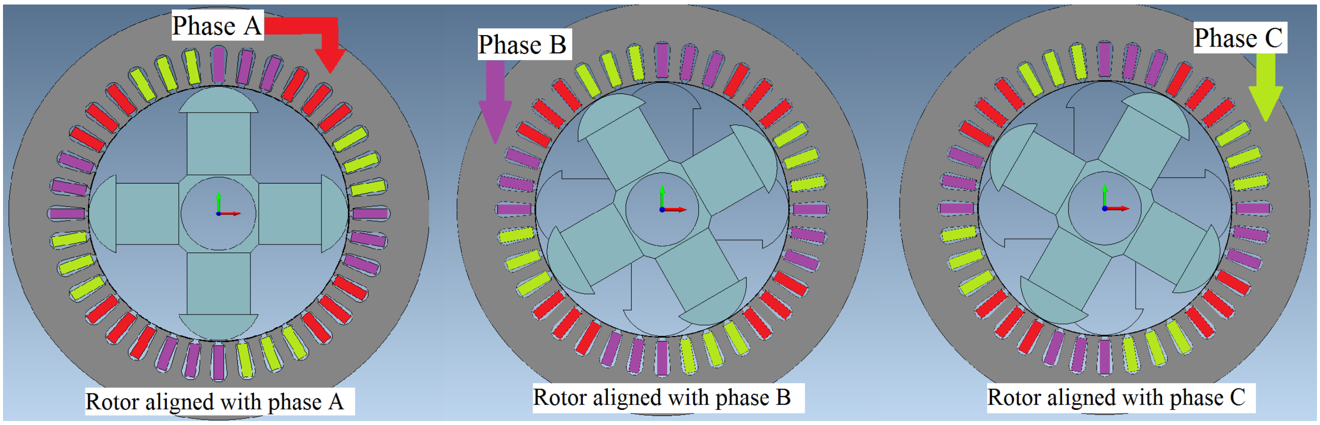


Fig. 1. Electric diagram of the synchronous machine under experimental testing.

Under symmetrical conditions and if the synchronous machine is healthy then the three independent phase currents will have the same amplitude and a phase difference 120°. As a result their instantaneous sum will cancel out the harmonics of ranks $(6k \pm 1)f_s$, where k is an integer and f_s the supply frequency. However, the triplets should remain and expected to have with low amplitudes due to the low voltage level which inflicts low saturation level in the machine's iron core.



a) b) c)

Fig. 2. The monitoring of each phase current at three different rotor positions where a) original position or 0°, b) rotor shifted by 120° and c) rotor shifted by -120°.

On the other hand, the local saturation and non-linear behaviour of the iron core, caused by the static eccentricity will cause an imbalance between the three independent phase currents. This imbalance will not affect significantly the fundamental harmonic of the phase currents mainly because the magnetic field asymmetry will be relatively small due to the small air gap. However, it is expected that the third harmonic of the phase currents will vary in both amplitude and phase. So, the summation of the three individual phase currents will result to a pseudo zero-sequence current with increased third harmonic. The monitoring of that amplitude is proposed here for the detection of the static eccentricity in salient pole synchronous machines.

III. Experimental Testing - Results and Analysis

A. Experimental Setup

To test the validity of the proposed eccentricity detection method, numerous laboratory tests were performed on a synchronous machine.

To produce the eccentricity in the synchronous machine one end bracket (bearing housing) was removed so the shaft is free in the non-drive end. By the use of two metallic profiles and two screws the shaft could be place in a fixed position. The horizontal and vertical air gap could be measured by the use of a comparator watch. So the eccentricity could be adjusted (Fig. 3). The current of the three phases are recorded through hall- effect current clamps (Fig. 4).

Fig. 3. Eccentricity adjustment mechanism.

Fig. 4. Complete experimental setup.

B. Results and Analysis

The synchronous machine has been measured under healthy and eccentric conditions. The applied levels of static eccentricity are 20%, 40%, 60% and 80%.

The first step is to analyse the phase difference between fundamental and third harmonic for each of the three individual currents and verify that the local magnetic field asymmetry is indeed causing a phase displacement of the third harmonic. This is accomplished by appropriate filtering. The Lissajous curves for the healthy case are shown below in Fig. 5 where the third harmonic is plotted versus the fundamental for each individual stator current. The third harmonic has a low phase difference close to zero degrees with its fundamental for the case of the first phase current. The phase difference is approximately 90° for the second phase current and 180° for the third phase. Considering that there is a phase difference 120° between the fundamental phase current harmonics, two of the three third phase harmonics are in phase while the last has 180° phase difference with the first two. That is because the stator is in Y and the instantaneous sum of the triplets is zero. The triplets are shown for the healthy case in Fig. 6.

On the other hand, Fig. 7 illustrates the Lissajous curves for the case of the salient pole machine with 20% static eccentricity. The phase differences are approximately 0° and 90° between the fundamental and its third harmonic as shown in Fig. 7-a and Fig. 7-b respectively. This is exactly the same as in the healthy synchronous machine. However, the third phase is different than the healthy machine. A significant shift of the third harmonic is observed which tends to be almost 90°. Following the same philosophy with the healthy machine and considering that there is a phase difference 120° between the fundamental phase current harmonics, it is now evident that all three phase third harmonics are now in phase (Fig. 8). This shows that the instantaneous sum of the three currents will be non-zero due to the asymmetry between the triplets.

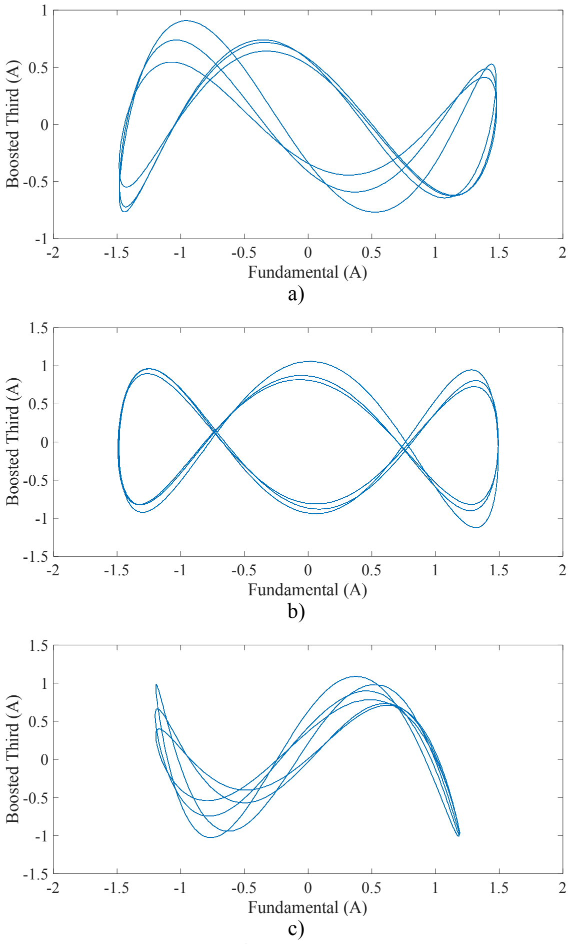


Fig. 5. Lissajous curves of: a) 1st phase current at initial rotor position, b) 2nd phase current when the rotor is shifted by 120° and c) 3rd phase current when the rotor is shifted by 240° versus their respective third harmonics (healthy machine).

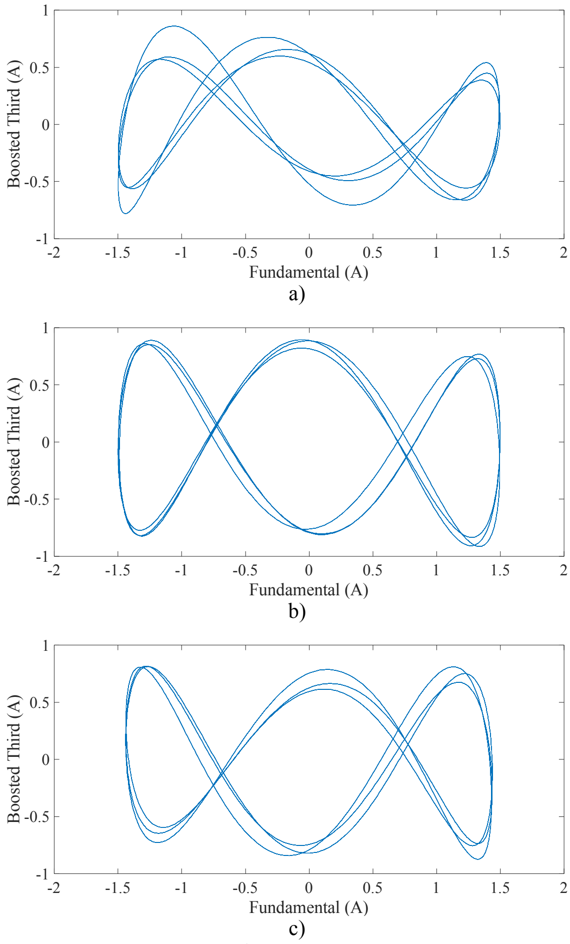


Fig. 7. Lissajous curves of: a) 1st phase current at initial rotor position, b) 2nd phase current when the rotor is shifted by 120° and c) 3rd phase current when the rotor is shifted by 240° versus their respective third harmonics (machine with 20% static eccentricity).

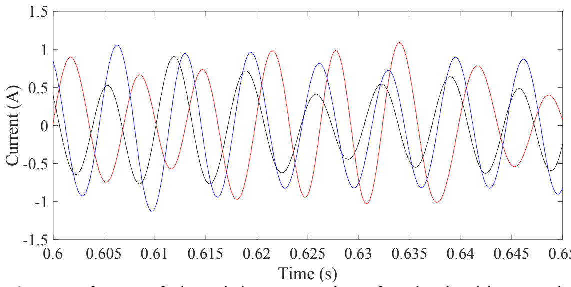


Fig. 6. Waveforms of the triplets over time for the healthy synchronous machine.

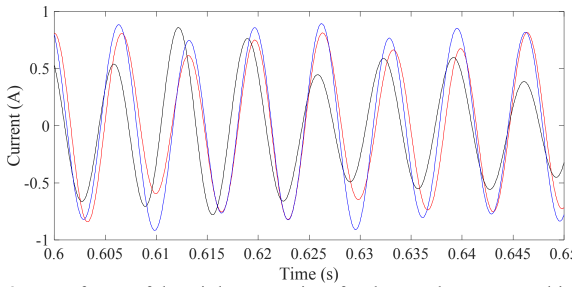
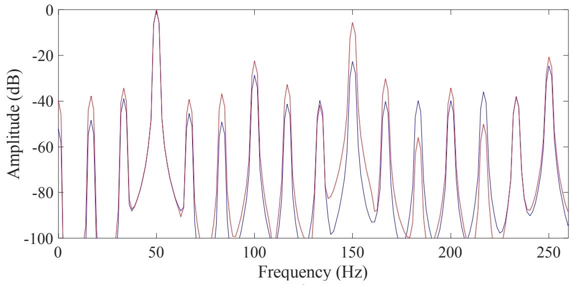
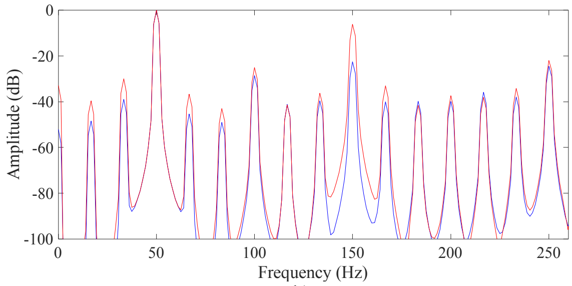


Fig. 8. Waveforms of the triplets over time for the synchronous machine with 20% static eccentricity.

A pseudo zero-sequence current is calculated for each studied case after adding up the three independent phase currents. The Fast Fourier Transform is then applied and the frequency spectra of the signals are calculated and shown in the following Fig. 9. The healthy machine's spectrum is with blue while the eccentric one with red colour. Due to non-ideality the third harmonic exists in the healthy machine and has an amplitude -22.57dB. However for all eccentric cases the amplitude of the third harmonic has been significantly increased (16.38dB-22dB). The same stands for the DC components of the signal. The healthy machine has a DC amplitude -52.18dB and it increases to -39.71dB for the machine with 20% static eccentricity while for the machine with 80% static eccentricity it reaches -22.55dB (approximately 30dB increase). Interestingly, the harmonics at: $f_s \pm \frac{f_s}{3}$ increase monotonically their amplitude with the fault level severity. The harmonics amplitudes are summarized in the following Table II.



a)



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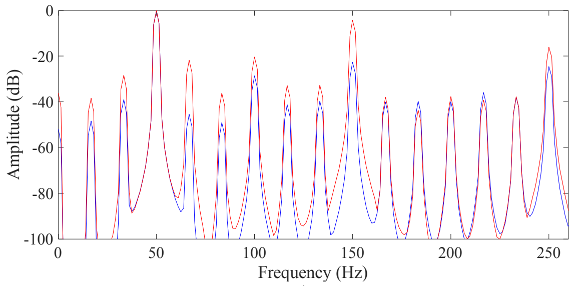
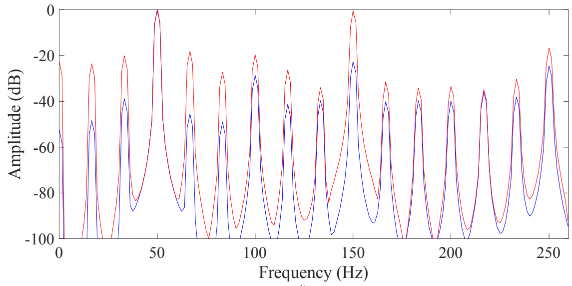


c)



d)

Fig. 9. Frequency spectra of the pseudo zero-sequence current of the machine with: a) 20%, b) 40%, c) 60% and d) 80% static eccentricity (red colour) in comparison with the healthy machine (blue colour).

TABLE II
HEALTHY AND ECCENTRIC MACHINE HARMONICS AMPLITUDES

		Amplitude (dB)				
Harmonic	Frequency (Hz)	healthy	20% SE	40% SE	60% SE	80% SE
3fs	150	-22.57	-5.613	-6.188	-4.264	-0.4725
DC	0	-52.18	-39.71	-33	-36.37	-22.55
fs-fs/3	33.33	-38.95	-34.26	-29.99	-28.34	-20.15
fs+fs/3	66.67	-45.42	-39.31	-36.67	-21.73	-18.14

IV. CONCLUSIONS

The paper presents a new off-line methodology to detect static eccentricity in salient pole synchronous machines. The proposed method relies on the monitoring of the stator phase currents at three different locked rotor positions an then the calculation of a pseudo zero-sequence current. It is shown with experimental testing that the third harmonic increases significantly in this signal when there is a static eccentricity fault. Other harmonics increase also and may be used for additional reliability of the proposed method. The advantages of this method is that it is non-intrusive while assesses the overall static eccentricity of the machine including the inclined one, a case not covered by conventional stray flux methods. Future work will focus on the electromagnetic analysis of the machine under the proposed test and the quantification of the saturation effect and overall iron core non-linear magnetisation on the third harmonic amplitude of the pseudo zero-sequence current.

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VI. Biographies

Konstantinos N. Gyftakis was born in Patras, Greece, in May 1984. He received the Diploma in Electrical and Computer Engineering from the University of Patras, Patras, Greece in 2010. He pursued a PhD in the same institution in the area of electrical machines condition monitoring and fault diagnosis (2010-2014). Then he worked as a Post-Doctoral Research Assistant in the Dept. of Engineering Science, University of Oxford, UK (2014-2015).

Since 2015 he has been a Lecturer on Electrical and Electronic Engineering, School of Computing, Electronics and Mathematics, Faculty of Engineering, Environment and Computing, Coventry University, UK. He is also an Associate Member of the Institute for Future Transport and Cities, Coventry, UK and a Member of the “Centro de Investigação em Sistemas Electromecatrónicos” (CISE), Portugal.

His research interests focus in the fault diagnosis, condition monitoring and degradation of electrical machines. He has authored/co-authored more than 60 papers in International scientific journals and conferences.

Carlos A. Platero was born in Madrid, Spain, in 1972. He obtained the Dipl. degree and Ph.D. degree in electrical engineering from Universidad Politécnica de Madrid, Spain, in 1996 and 2007 respectively. Since 1996 to 2008 he has worked in ABB Generación S.A., Alstom Power S.A. and ENDESA Generación SA, always involved in design and commissioning of power plants. In 2002 he began teaching at the Electrical Engineering Department of the Universidad Politécnica de Madrid, and joined an energy research group. Since 2008 he became full-time Associate Professor.

Santiago Bernal was born was born in Madrid, Spain, in 1995. He obtained the Dipl. degree in energy engineering from Universidad Politécnica de Madrid, Spain, in 2017. Then he started to work in the electrical machines laboratory where he was involved in research projects related to monitoring and protection of electrical machines.