Investigations on the behavioral analysis of unbalanced synchronous generators

Djilali Kouchih[1], Redouane Hachelaf[1,2], Mohamed Tadjine[2], Mohamed Seghir Boucherit[2]
[1]Automatic and Electrotechnic Department, University Blida 1, Blida, Algeria
[2]Automatic Control Department, National Polytechnic School, Alger, Algeria

Article Info

Article history:

Received Feb 24, 2024
Revised May 4, 2024
Accepted May 22, 2024

Keywords:

Fast Fourier transform
Modeling
Neutral voltage
Synchronous generators
Unbalanced conditions

ABSTRACT

This paper describes a new methodology for the modeling and analysis of three-phase synchronous generators operating under an unbalanced regime. For this, an improved state model has been developed in order to determine significant signatures on stator and rotor electromagnetic quantities. This methodology is characterized by some advantages. Firstly, it can be generalized for the modeling of severe defects like open-phase and short circuits. Furthermore, by comparison to classical approaches based on the finite elements and symmetrical components methods, this approach gives a good compromise between precision and simulation time. The obtained results show the effectiveness of this approach for the analysis of unbalanced synchronous generators.

Corresponding Author:

Djilali Kouchih
Automatic and Electrotechnic Department, University Blida 1
Blida 09000, Algeria
Email: djkouchih@yahoo.fr

1. INTRODUCTION

Due to their stable performance, synchronous machines are frequently exploited as generators in electrical energy production, especially in high-power systems. These generators are subject to different asymmetries. The most encountered are the stator asymmetries which are mainly due to the short-circuit faults and unbalanced load conditions. The modeling of unbalanced synchronous generators (USG) makes it possible to predict the abnormal function under unbalanced conditions [1]-[5]. To validate this approach, the unbalanced load conditions have been considered.

Modeling and detection of dysfunctions in electrical machines is an important area of research for both industrial and scientific researchers. For this, the well-known approach consists of processing a monitoring signal [6]-[15]. Regarding this approach, the main drawback is to choose the convenient signal that makes it possible to discriminate asymmetries characterized by similar signatures. The second approach uses the analysis of a residual signal [16]-[18]. This approach can generate false alarms due to the sensitivity to model parameters. Recently, the advanced approach has been based on intelligent techniques. The serious drawback of this approach is its complexity for implementation [19]-[22].

Systems monitoring research often requires a precise model. The most used approaches are the finite elements and symmetrical components methods [23], [24]. In this work, a state model has been developed considering neutral voltage. This approach is characterized by some advantages. Firstly, it can be generalized for the modeling of severe defects like open-phase and short circuits. Furthermore, by comparison to classical approaches based on the finite elements and symmetrical components methods, this approach gives a good compromise between precision and simulation time. The obtained results show the effectiveness of this methodology for the behavioral analysis of USG.

2. USG STATE MODEL

For USG, the stator voltage equation is expressed by (1)-(6) [25].

$$\frac{d[\Phi sd]}{dt} = [usd] + [Rsd][isd] \quad (1)$$

With:

$$[usd] = [Td][vn] \quad (2)$$

$$[\Phi sd] = [Td][\Phi s] \quad (3)$$

$$[Rsd] = [Td][Rs] \quad (4)$$

$$[Td] = \begin{bmatrix} +1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & +1 \end{bmatrix} \quad (5)$$

$$[vn] = [Rl][isd] \quad (6)$$

$[\Phi s]$,$[isd]$, $[vn]$are respectively the vector of the stator flux, stator currents, and load voltages, $[Rs]$, $[Rl]$ are respectively the matrix of the stator and load resistances. The rotor voltage equation is expressed by (7).

$$\frac{d\Phi_r}{dt} = Vr - Rrir \quad (7)$$

To establish the state model of the USG, it’s important to express the machine currents in terms of the machine fluxes. For this, we define a vector of two independent currents as illustrated by (8) [25].

$$[iabs] = \begin{bmatrix} ias \\ ibs \end{bmatrix} \quad (8)$$

The stator and rotor fluxes are calculated using (9)-(13),

$$[\Phi abs] = -[Lsd][iabs] - [Lsrd]ir \quad (9)$$

$$\Phi r = -[Lrsd][iabs] - Lr.ir \quad (10)$$

$$[\Phi abs] = [Asd][\Phi s] \quad (11)$$

with (12) and (13).

$$[Asd] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \quad (12)$$

$$[Bsd] = \begin{bmatrix} +1 & 0 \\ 0 & +1 \\ -1 & -1 \end{bmatrix} \quad (13)$$

$[Lss]$ is the matrix of the stator inductances; $[Lsr]$ is the matrix of the stator-rotor mutual inductances; ir is the field current; and Lr, Rr are respectively the inductance and resistance of the rotor winding. Therefore, the stator and rotor currents are expressed by (14)-(19).

$$[iabs] = -\left([Lsd] - \frac{1}{Lr}[Lsrd][Lrsd]\right)^{-1}\left([\varphi abs] - [Lsrd]\frac{\Phi r}{Lr}\right) \quad (14)$$

$$ir = -(Lr - [Lrsd][Lsd]^{-1}[Lsrd])^{-1}(\Phi r - [Lrsd][Lsd]^{-1}[\varphi abs]) \quad (15)$$

$$[Lsd] = [Asd][Ls][Bsd] \quad (16)$$

$$[Lsrd] = [Asd][Lsr] \quad (17)$$

$$[Lrsd] = [Lrs][Bsd] \quad (18)$$

$$[Lrs] = [Lsr]^T \quad (19)$$

From (1), (8), (14), and (15), the USG state model will be expressed by (20) and (21).

$$\begin{cases} \frac{d[\Phi sd]}{dt} = -[Rsd][Bsd]\left([Lsd] - \frac{1}{Lr}[Lsrd][Lrsd]\right)^{-1}\left([As][\Phi sd] - [Lsrd]\frac{\Phi r}{Lr}\right) + [usd] \\ \frac{d\Phi_r}{dt} = Vr + R_r(Lr - [Lrsd][Lsd]^{-1}[Lsrd])^{-1}(\Phi r - [Lrsd][Lsd]^{-1}[As][\Phi sd]) \\ J\frac{d\Omega}{dt} = Tm - Te - fv\Omega \end{cases} \quad (20)$$

The electromagnetic torque is expressed by (21).

$$Te = \frac{P}{2}[is]^T\frac{\partial[Lsr]}{\partial\theta}ir \quad (21)$$

T_m is the input torque; J is the inertia; fv is the viscose friction coefficient. The neutral voltage v_{on} is calculated using (22) to (23) [25].

$$von = \frac{\sum_{i=a,b,c}(vin - vio)}{3}, i = a, b, c \quad (22)$$

Where the stator voltages are calculated by (23) [25].

$$vin = risiis + \frac{\Delta\varphi is}{Ts}, i = a, b, c \quad (23)$$

T_s is the sampling time.

3. SIMULATIONS

Using MATLAB, the state model is simulated for a synchronous generator of 1.5 kVA, 4/2.3 A, 220/380 V – 50 Hz. At t = 0, the field current is established with no load conditions (open stator). After that, the balanced load of 110 Ω is connected to the generator at t = 0.25 s. An unbalanced load of r_{al} = 220 Ω, r_{bl} = r_{cl} = 110 Ω is selected at t = 0.5 s. The stator, currents, and their fast Fourier transform (FFT) are shown by Figures 1(a)-1(d) (see Appendix), respectively. The field current and electromagnetic torque are shown in Figures 1(e)-1(f) (see Appendix), respectively. Figures 1(g) and 1(h) (see Appendix) show the neutral voltage and its spectrum analysis, respectively.

Simulation results show that distortion is produced through the temporary voltages and currents as illustrated by Figures 1(a) and 1(c), respectively. As mentioned in Figures 1(b) and 1(d), the spectrum analysis shows that some harmonics of impaired orders (150 Hz, 250 Hz, …) are generated over the stator voltages and currents. Due to the magnetic interaction between stator and rotor circuits, the field current is affected as illustrated by Figure 1(e). Figure 1(f) shows that a pulsating torque is created causing undesirable effects such as vibration, noise, and heating of the unbalanced generators. Regarding the neutral voltage, it is about 65 V as shown in Figure 1(g). Figure 1(h) shows that specific harmonics of impaired orders are observed through the spectrum analysis of the neutral voltage.

4. EXPERIMENTS

An experimental test has been conducted on a three-phase synchronous generator of 1.5 kVA, 4 / 2.3 A, 220/380 V – 50 Hz. The rotor current is established with open stator. After that, a balanced load of 110 Ω is connected to the generator. Asymmetrical load of r_{al} = 220 Ω, r_{bl} = r_{cl} = 110 Ω is considered. The neutral voltage and its spectrum analysis are illustrated in Figures 2(a) and 2(b) respectively. Figures 2(c) and 2(d) illustrate the spectrum analysis of the stator voltages and currents respectively.

For an unbalanced load, the neutral voltage reaches about 55 V as illustrated by Figure 2(a). Figure 2(b) shows the FFT of the neutral voltage where specific harmonics of impaired orders are generated. These harmonics are similar to the harmonics of the stator voltages and currents as illustrated by Figures 2(c) and 2(d), respectively.

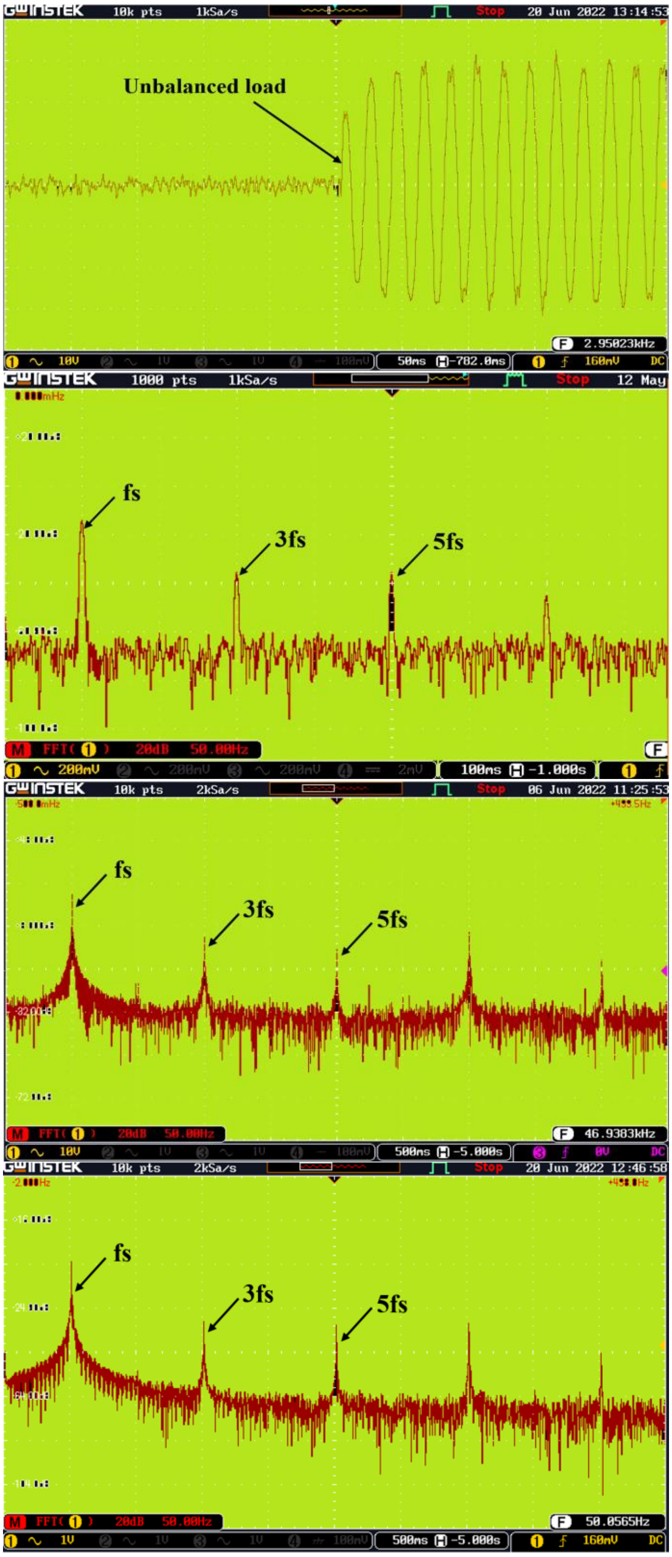

Figure 2. USG experimental results: (a) neutral voltage, (b) FFT of neutral voltage, (c) FFT of stator voltages, and (d) FFT of stator currents

5. CONCLUSIONS

A new methodology has been investigated for the behavioral analysis of the USG. To test the validity of this methodology, unbalanced load has been considered. Severe effects are mentioned like vibration, noise, and excessive heating of the USG. For this reason, it's mandatory to avoid all asymmetries before they lead to a progressive destruction of the generators. The FFT of the neutral voltage, stator voltages, and currents have been proposed for the detection of stator asymmetries. This work may be extended to several faults like open-phase and short-circuits.

APPENDIX

(a) (b) (c) (d)

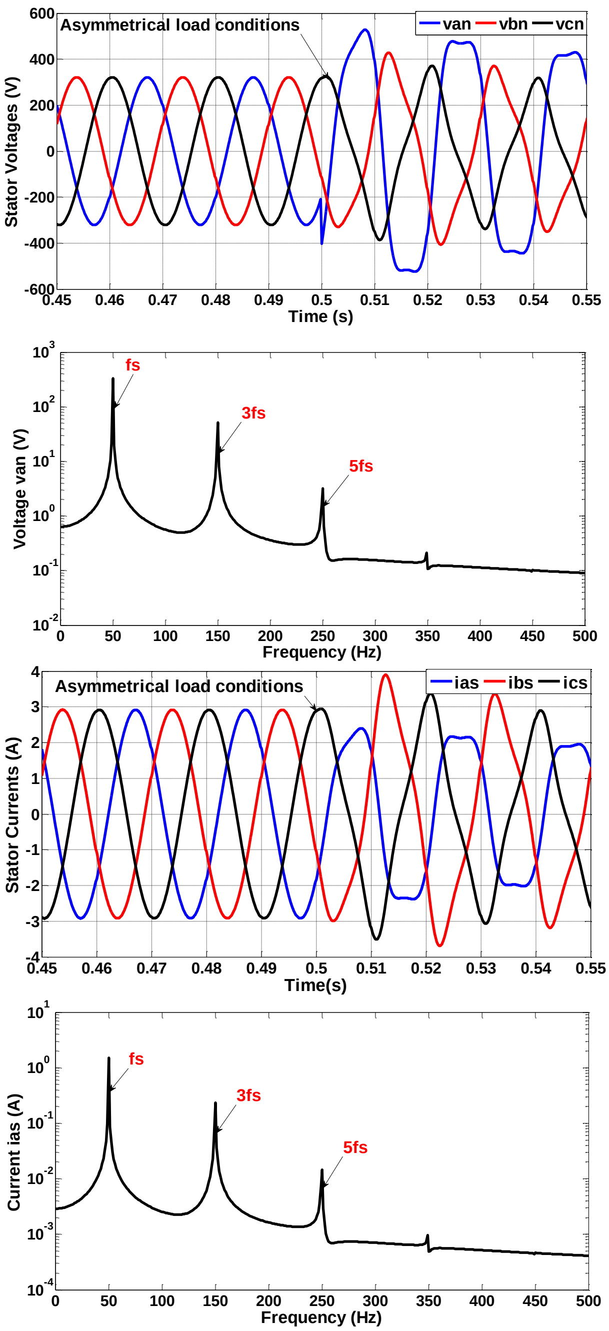

Figure 1. USG simulation results: (a) stator voltages, (b) FFT of stator voltages, (c) stator currents, and (d) FFT of stator currents

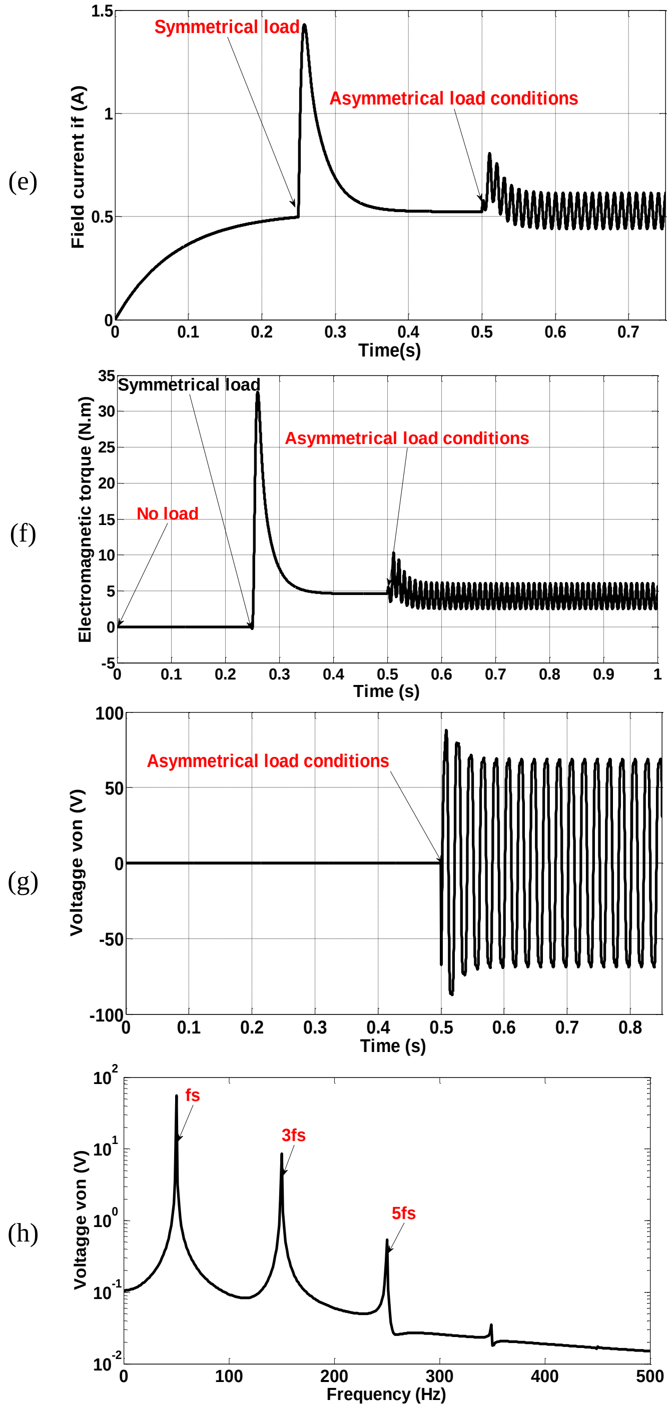

Figure 1. USG simulation results: (e) field current, (f) electromagnetic torque, (g) neutral voltage, and (h) FFT of neutral voltage (continued)

REFERENCES

[1] M. Rida, E. Rashad, A. El Samahy, M. El Koroflly, and E. Youssef, "Performance analysis of a stand-alone synchronous reluctance generator under unbalanced conditions," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 1, pp. 140–152, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp140-152.

[2] H.-T. Pham, J.-M. Bourgeot, and M. E. H. Benbouzid, "Comparative investigations of sensor fault-tolerant control strategies performance for marine current turbine applications," *IEEE Journal of Oceanic Engineering*, vol. 43, no. 4, pp. 1024–1036, Oct. 2018, doi: 10.1109/JOE.2017.2747018.

[3] M. H. Mousavi and H. M. CheshmehBeigi, "A brief review of methods for improving the performance of virtual synchronous generators under unbalnced conditions," in *2022 30th International Conference on Electrical Engineering (ICEE)*, IEEE, May 2022, pp. 630–635. doi: 10.1109/ICEE55646.2022.9827134.

[4] F. Haidar, T. S. Douiri, and T. Bartoli, "Open-circuit fault detection of inverter fed PMSM for electrical powertrain applications," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 2, pp. 741–753, Jun. 2023, doi: 10.11591/ijpeds.v14.i2.pp741-753.

[5] A. L. Shuraiji, "The effect of static and dynamic eccentricities on the performance of flux reversal permanent magnet machine," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 11, no. 2, pp. 634–640, Jun. 2020, doi: 10.11591/ijpeds.v11.i2.pp634-640.

[6] N. M. A. Freire, J. O. Estima, and A. J. M. Cardoso, "A new approach for current sensor fault diagnosis in PMSG drives for wind energy conversion systems," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1206–1214, Mar. 2014, doi: 10.1109/TIA.2013.2271992.

[7] E. Awada, A. Al-Qaisi, E. Radwan, and M. Nour, "Motor fault detection using sound signature and wavelet transform," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 13, no. 1, pp. 247–255, Mar. 2022, doi: 10.11591/ijpeds.v13.i1.pp247-255.

[8] H. Ehya, A. Nysveen, and J. A. Antonino-Daviu, "Advanced fault detection of synchronous generators using stray magnetic field," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 11, pp. 11675–11685, Nov. 2022, doi: 10.1109/TIE.2021.3118363.

[9] A. Mohammed, J. I. Melecio, and S. Djurovic, "Electrical machine permanent magnets health monitoring and diagnosis using an air-gap magnetic sensor," *IEEE Sensors Journal*, vol. 20, no. 10, pp. 5251–5259, May 2020, doi: 10.1109/JSEN.2020.2969362.

[10] J. Hang *et al.*, "A voltage-distortion-based method for robust detection and location of interturn fault in permanent magnet synchronous machine," *IEEE Transactions on Power Electronics*, vol. 37, no. 9, pp. 11174–11186, Sep. 2022, doi: 10.1109/TPEL.2022.3167439.

[11] C. Carunaiselvane, T. R. Chelliah, and S. V. A. Sarma, "Negative sequence current in megawatt hydro generators at uprated unbalanced loads," in *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, IEEE, Dec. 2018, pp. 1–6. doi: 10.1109/PEDES.2018.8707919.

[12] K. Al Jaafari, A. Negahdari, H. A. Toliyat, N. Safari-Shad, and R. Franklin, "Modeling and experimental verification of a 100% stator ground fault protection based on adaptive third-harmonic differential voltage scheme for synchronous generators," *IEEE Transactions on Industry Applications*, vol. 53, no. 4, pp. 3379–3386, Jul. 2017, doi: 10.1109/TIA.2017.2682165.

[13] C. Wang, X. Liu, and Z. Chen, "Incipient stator insulation fault detection of permanent magnet synchronous wind generators based on Hilbert–Huang transformation," *IEEE Transactions on Magnetics*, vol. 50, no. 11, pp. 1–4, Nov. 2014, doi: 10.1109/TMAG.2014.2318207.

[14] A. B. Mugarra, C. A. Platero, J. A. Martinez, and U. Albizuri-Txurruca, "Validity of frequency response analysis (FRA) for diagnosing large salient poles of synchronouos machines," *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 226–234, 2019, doi: 10.1109/TIA.2019.2949982.

[15] H. Mayora, A. Mugarra, J. M. Guerrero, and C. A. Platero, "Synchronous salient poles fault localization by SFRA and fault diagram method," *IEEE Transactions on Energy Conversion*, vol. 37, no. 4, pp. 2669–2677, Dec. 2022, doi: 10.1109/TEC.2022.3182817.

[16] B. Aubert, J. Regnier, S. Caux, and D. Alejo, "Kalman-filter-based indicator for online interturn short circuits detection in permanent-magnet synchronous generators," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 3, pp. 1921–1930, Mar. 2015, doi: 10.1109/TIE.2014.2348934.

[17] A. Mahmoudi, I. Jlassi, A. J. M. Cardoso, K. Yahia, and M. Sahraoui, "Inter-turn short-circuit faults diagnosis in synchronous reluctance machines, using the Luenberger State observer and current's second-order harmonic," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 8, pp. 8420–8429, Aug. 2022, doi: 10.1109/TIE.2021.3109514.

[18] J. E. Stellet and T. Rogg, "On linear observers and application to fault detection in synchronous generators," *Control Theory and Technology*, vol. 12, no. 4, pp. 345–356, Nov. 2014, doi: 10.1007/s11768-014-3036-z.

[19] J. Hang, X. Shu, S. Ding, and Y. Huang, "Robust open-circuit fault diagnosis for PMSM drives using wavelet convolutional neural network with small samples of normalized current vector trajectory graph," *IEEE Transactions on Industrial Electronics*, vol. 70, no. 8, pp. 7653–7663, Aug. 2023, doi: 10.1109/TIE.2022.3231304.

[20] R. A. Ahouee and M. Mola, "Inter-turn fault detection in PM synchronous motor by neuro-fuzzy technique," *International Journal of System Assurance Engineering and Management*, vol. 11, no. 5, pp. 923–934, Oct. 2020, doi: 10.1007/s13198-020-01019-1.

[21] W. Wang, J. Taylor, and R. J. Rees, "Recent advancement of deep learning applications to machine condition monitoring part 1: a critical review," *Acoustics Australia*, vol. 49, no. 2, pp. 207–219, Jun. 2021, doi: 10.1007/s40857-021-00222-9.

[22] J. Cen, Z. Yang, X. Liu, J. Xiong, and H. Chen, "A review of data-driven machinery fault diagnosis using machine learning algorithms," *Journal of Vibration Engineering & Technologies*, vol. 10, no. 7, pp. 2481–2507, Oct. 2022, doi: 10.1007/s42417-022-00498-9.

[23] C. P. Salomon *et al.*, "Discrimination of synchronous machines rotor faults in electrical signature analysis based on symmetrical components," *IEEE Transactions on Industry Applications*, vol. 53, no. 3, pp. 3146–3155, May 2017, doi: 10.1109/TIA.2016.2613501.

[24] X. Liang, M. Z. Ali, and H. Zhang, "Induction motors fault diagnosis using finite element method: a review," *IEEE Transactions on Industry Applications*, vol. 56, no. 2, pp. 1205–1217, Mar. 2020, doi: 10.1109/TIA.2019.2958908.

[25] D. Kouchih, R. Hachelaf, M. Tadjine, and M. S. Boucherit, "Electromagnetic analysis and electrical signature based detection of stator asymmetries in permanent magnet synchronous generators," in *2023 IEEE International Conference on Artificial Intelligence & Green Energy (ICAIGE)*, IEEE, Oct. 2023, pp. 1–5. doi: 10.1109/ICAIGE58321.2023.10346466.

BIOGRAPHIES OF AUTHORS

Djilali Kouchih is an associate professor in Automatic and Electrotechnics Department at the University Blida 1, Algeria. He received the engineer degree, the Ph.D. degree in Electrical Engineering from the National Polytechnics School, of Algiers, Algeria, in 1994, and 2015 respectively. His research interests are in the area of electrical drives, process control, diagnosis, and renewable energies. He can be contacted at email: djkouchih@yahoo.fr.

Redouane Hachelaf is an assistant professor in Automatic and Electrotechnic Department at the University Blida 1, Algeria. He received the engineer degree from the University of Medea in 2008, the magister degree from the Military Polytechnics School, Bordj El Bahri, Algeria in 2011. Currently, he is Ph.D. student in automatic control at the National Polytechnics School, Algiers, Algeria. He can be contacted at email: haclefr@yahoo.fr.

Mohamed Tadjine is with the Department of Automatic Control at the National Polytechnics School of Algiers, Algeria, where he is currently professor. He received the engineering degree from the National Polytechnic of Algiers, Algeria, in 1990 and the Ph.D. degree in automatic control from The National Polytechnic Institute of Grenoble (INPG), France in 1994. From 1995 to 1997, he was a researcher at the automatic systems laboratory, Amiens, France. His main research areas are: nonlinear and robust control, observer design, fault detection and fault tolerant control, robotics, and electrical drives and quantum computing. He can be contacted at email: tadjine@yahoo.fr.

Mohamed Seghir Boucherit is a professor and head of Industrial Systems and Diagnosis Team of the Process Control Laboratory in the Department of Automatic Control the National Polytechnics School, Algiers, Algeria. He received the engineer degree in Electrotechnics, the magister degree and the Ph.D. degree in Electrical Engineering, from the National Polytechnics School, Algiers, Algeria, in 1980, 1988, and 1995 respectively. His research interests are in the area of electrical drives, process control, and diagnosis. He can be contacted at email: msboucherit@gmail.com.