Analysis of Wavelet Controller for Robustness in Electronic Differential of Electric Vehicles: An Investigation and Numerical Developments

Febin J. L. Daya,1 Padmanaban Sanjeevikumar,2 Frede Blaabjerg,3 Patrick W. Wheeler,4 Joseph Olorunfemi Ojo,5,6 and Ahmet H. Ertas7

1School of Electrical and Electronics Engineering, Vellore Institute of Technology University, Chennai, India
2Department of Electrical and Electronics Engineering, University of Johannesburg, Auckland Park, Johannesburg, South Africa
3Department of Energy Technology, Aalborg University, Aalborg, Denmark
4Power Electronics, Machines and Control Group, Department of Electrical and Electronics Engineering, Nottingham University, Nottingham, United Kingdom
5Center for Energy System Research, Department of Electrical and Computer Engineering, Tennessee Technical University, Cookeville, Tennessee, USA
6Eskom Centre of Excellence in HVDC Engineering, University of KwaZulu-Natal, Durban, South Africa
7Biomedical Engineering Department, Engineering Faculty, Karabuk University, Demir-Celik Campus, Karabuk, Turkey

CONTENTS
1. Introduction
2. System Modeling of Electronic Differential and BLDC Motor
3. WT-based Speed Controller
4. Numerical Simulation Test Results and Discussions
5. Conclusions
References

Keywords: electronic differential, electric vehicle, wavelet controller, traction control, brushless DC motor, mechanical differential, electronic differential, proportional integral differential controller, fuzzy logic, neural wavelet system

ABSTRACT—In road transportation systems, differential plays an important role in preventing the vehicle from slipping on curved tracks. In practice, mechanical differentials are used, but they are bulky because of their increased weight. Moreover, they are not suitable for electric vehicles, especially those employing separate drives for both rear wheels. The electronic differential constitutes recent technological advances in electric vehicle design, enabling better stability and control of a vehicle on curved roads. This article articulates the modeling and simulation of an electronic differential employing a novel wavelet transform controller for two brushless DC motors ensuring drive in two right and left back driving wheels. Further, the proposed work uses a discrete wavelet transform controller to decompose the error between actual and command speed provided by the electronic differential based on throttle and steering angle as the input into frequency components. By scaling these frequency components by their respective gains, the obtained control signal is actually given as input to the motor. To verify the proposal, a set of designed strategies were carried out: a vehicle on a straight road, turning right and turning left. Numerical simulation test results of the controllers are presented and compared for robust performance and stability.

1. INTRODUCTION

Due to increasing world population, the demand for automobiles has also drastically increased, with safety on the road becoming a major concern. A differential in the transmission system in an automobile plays an important role in preventing a vehicle from slipping on curved roads. Conventional automobiles make use of a mechanical gear train for their functioning,
but mechanical differentials are bulky due to their increased weight and are not suitable for electric vehicles (EVs), especially those employing separate drives for both rear wheels. An electronic differential constitutes technological advances in EV design and ensures stability and better control on curved roads. Further, electronic differentials have a longer lifespan as they are programmed devices controlling the individual speeds of motors. The increasing popularity of EVs is due to their reduced emissions (free of pollution), reduction in fuel consumption, weightlessness, and lack of bulk; it performs all functions of the mechanical differential and hence has a bright future.

For improving air quality and keeping traffic problems in check, neighborhood EVs (NEVs) are the best known solution for personal transportation [1]. Implementation has been carried out for NEVs with two different wheel drives via induction motors using a digital signal processor, where both the current and speed controllers are standard proportional integral differential (PID) controllers; it was verified that by concentrating all control variables in the same memory, the system robustness was highly improved [1]. A field-programmable gate array (FPGA) based integrated control system for NEV AC motor drives was investigated, and it was shown that exploiting the parallel processing capabilities of an FPGA to execute several control schemes did not compromise overall system performance [2]. Renowned control methods, such as fuzzy logic, have been employed in the speed controller to fine-tune the slip rate of each wheel of the EV, verifying smooth propagation on straight and curved roads [3]. The advantage of fuzzy controllers is that they do not require prior information about the mathematical model of the plant.

Electronic differentials have been used to control motors with a speed controller governed by a PID or fuzzy controller [1–7]. Recently, discrete wavelet transform (DWT) has replaced PID controllers with its technological robustness [8–14]. Wavelet transform (WT) has found applications in AC drives, performing much better than standard Pulse Width Modulation (PWM) techniques in experimental verifications [8, 9]. WT techniques have also been extended to AC motor applications [10–14], in particular to control electric vehicles (EVs). For steering control of EVs, fuzzy-neural control WT algorithms have been implemented (AC motor drives) [15]. Also WT has been applied successfully for energy management system in plug-in hybrid EVs (HEVs) [16]. Recently, WT was effectively extended to fault diagnostics in multi-level power converters during short-circuit condition-based adaptive neural-fuzzy interface systems [17, 18].

To exploit the advantages of WT, this work articulates an electronic differential employing two AC motors ensuring the drive of both rear wheels is carried out in MATLAB/Simulink software (The MathWorks, Natick, Massachusetts, USA). The set of obtained results is provided with a comparison between PID and WT controllers for robustness and stability under strategically designed conditions of an EV driving on curved roads.

This research is organized as follows. Section 2 describes the dynamics of the system modeling of an electronic differential and BLDC motor. DWT based on the speed controller, the selection of WT, the level of decomposition, and the WT electronic differential of the EV are described in Section 3. The complete set of numerical simulation test results along with performances indices obtained, based on three different strategically designed driving conditions on curved roads, are given in Section 4; where factors affecting WT controller functioning and stability verification by Bode plots are also given. Finally, the conclusions of this article are given in Section 5.

2. SYSTEM MODELING OF ELECTRONIC DIFFERENTIAL AND BLDC MOTOR

The design of an electronic differential should permit the vehicle to transverse a curved path or road without slipping. For this purpose, two inputs are necessary: steering angle and throttle position. To avoid slipping and collapse of the vehicle, these two functions decide the the speed of the right and left wheels during propagation [15, 16].

Figure 1(a) illustrates the schematic of an EV with the electronic differential under investigation. Here each wheel is controlled by two independent motors. In the case of a right turn, the differential will have to retain left wheel at a higher speed than the right, which keeps the tires from losing traction on turning (right) and vice versa (left) [18]. Figure 1(b) illustrates the EV turn on curved roads [18], where $L_w$ is the wheel base, $\delta$ is the turning angle, $d_w$ is the track width, $R$ is the radius of the turn, and $\omega_R$ and $\omega_L$ represent the angular speeds of the left and the right wheels, respectively. By the function of vehicle speed and turn radius, the linear speed of each wheel is stated as

$$v_L = \omega_r \left( R + \frac{d_w}{2} \right).$$

$$v_R = \omega_r \left( R - \frac{d_w}{2} \right).$$

The expression relating turn radius, steering angle, and wheel base is given by

$$R = \frac{L_w}{\tan \delta}. $$

$$764$$

Electric Power Components and Systems, Vol. 44 (2016), No. 7
Now the difference in angular speeds between wheel drives is written as
\[
\Delta \omega = \omega_r - \omega_l = \frac{d_w \tan \delta}{L_w} \omega_v.
\] (6)

The direction of the turn is decided by the sign of the steering, which is actually given by:
- for right turns, \( \delta > 0 \);
- for left turns, \( \delta < 0 \);
- for going straight, \( \delta = 0 \).

The driver provides the steering input, and the electronic differential executes the immediate action by reducing inner wheel's speed and increases outer wheel's speed. Now, the wheels' driving speeds are expressed as
\[
\omega_r^* = \omega_v + \frac{\Delta \omega}{2},
\]
(7)
\[
\omega_l^* = \omega_v - \frac{\Delta \omega}{2}.
\]
(8)

In standard drive, BLDC motors are widely used in EVs, and two types of BLDC motors are used in practice: the interior-rotor type and the outer-rotor type, both of which are made of permanent magnets (rotor). In a BLDC motor, the number of magnet pieces is equal to the motor pole numbers, and phase windings are distributed on stators to form trapezoidal-shaped back-electromotive force (EMF). Such benefits as increased efficiency, higher torque density, noiseless operation, and less maintenance have attracted BLDC motors to EV propulsion.

The mathematical model of three phase BLDC motors as shown in Figure 2 can be described by the following equation:

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix} = \begin{bmatrix}
0 & R & 0 \\
R & 0 & 0 \\
0 & 0 & R
\end{bmatrix} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \frac{d}{dt} \begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} + \begin{bmatrix}
e_a \\
e_b \\
e_c
\end{bmatrix}.
\]

### 3. WT-BASED SPEED CONTROLLER

The schematics of an indirect field-oriented control (IFOC) wavelet speed control scheme for a BLDC motor is given in Figure 3 [11–14]. For sensitive speed regulation for both the right and left motors, WT is employed to each speed controller. The type of WT and number of decomposition levels are two criteria for WT controllers.

The resolution of DWT is changed by filtering operations, and the scales are changed by down sampling operations; a typical two-level decomposition tree is shown in Figure 4.
Decomposition occurs if a discrete signal $x[n]$ of length $N$ is transferred to a high-pass filter, resulting in impulse response $h[n]$ and, accordingly, a low-pass filter results in impulse response $g[n]$. A one-level DWT decomposition is obtained by high- and low-pass filter outputs. The so-called mathematical expression can be given as [10–14, 19, 20]:

$$d_1[n] = \sum_{k=0}^{N-1} x[k] h[n-k], \quad (9)$$

$$a_1[n] = \sum_{k=0}^{N-1} x[k] g[n-k], \quad (10)$$

where $d_1[n]$ and $a_1[n]$ are the high- and low-pass filter outputs, respectively. On the other hand, the two-level decomposition of the discrete signal is down sampled mathematically as

$$d_2[n] = \sum_{k=0}^{N/2-1} a_1[k] h[n-k], \quad (11)$$

$$a_2[n] = \sum_{k=0}^{N/2-1} a_1[k] g[n-k]. \quad (12)$$

### 3.1. Selection of Wavelet Function

Several types of WT are available, but the selection depends on what signal fits the applications. For this investigation, the WT analysis is applied to the error signal for the BLDC drive. For this purpose, minimum description length (MDL) data criterion is selected to be the best WT filter. The optimal number of WT coefficients to be retained for signal reconstruction can be mathematically expressed as [19]

$$MDL(k, n) = \min \left\{ \frac{3}{2} k \log N + \frac{N}{2} \log \left| \tilde{\alpha}_n - \alpha_n^{(k)} \right|^2 \right\},$$

$$0 < k < N; 1 \leq n \leq M \quad (13)$$

where $\tilde{\alpha}_n = W_n f$ denotes a vector of the WT-transformed coefficients of signal $f$ using WT filters ($n$), and $\alpha_n^{(k)} = \theta^k \tilde{\alpha}_n$.
\( \emptyset^K (W_n f) \) denotes a vector that contains \( k \) non-zero elements. Threshold parameter \( \emptyset^K \) keeps \( k \) number of the largest elements of the vector \( \tilde{\alpha}_n \) constant and sets all other elements to zero. \( N \) and \( M \) denote the length of the signal and the number of WT filters, respectively. By the MDL criterion, the orthogonal Daubechies WT filter db4 is selected for implementing the IFOC speed controller for this investigation study.

### 3.2. Levels of Decomposition

The number of levels of decomposition represents the gains of the controller, and for deducing this, an entropy-based criterion was used. Entropy \( H(x) \) for the same signal and having the same length \( N \) is stated as [10, 19]

\[
H(x) = - \sum_{n=0}^{N-1} |x(n)|^2 \log |x(n)|^2.
\]  

(14)

To determine the decomposition’s optimum levels, the entropy is calculated for both the old and new levels and compared as follows:

\[
H(x)_j \geq H(x)_{j-1}.
\]  

(15)

Further, the old level \( j \) is removed from the DWT tree. For the proposed investigation, two levels of decomposition are more sufficient and effective to represent the error signal [11–14].

### 3.3. Wavelet Controller for Electronic Differential of EV

Figure 5 shows the proposed control schematic of the WT IFOC. The steering angle and throttle position were taken as input for the electronic differential. The error detector compares the desired speed with the actual one and generates the error speed.

By the WT controller, the error signal is decomposed into its detailed and approximated components [11–14, 17, 21–22]; accordingly, these components are scaled by their respective gains, and to generate control signal \( u \), they are then added together as follows:

\[
u = k_{d1} e_{d1} + k_{d2} e_{d2} + \cdots + k_{dN} e_{dN} + k_{aN} e_{aN},
\]  

(16)

where gains \( k_{d1}, k_{d2}, \ldots, k_{dN} \) are used to tune the high- and medium-frequency components of the error signal \( (e_{d1}, e_{d2}, \ldots, e_{dN}) \), whereas gain \( k_{aN} \) is used to tune the low-frequency components of error signal \( (e_{aN}) \), and \( N \) is the number of decomposition levels.

It should be noted that the gain values of approximation coefficients \( (k_{aN}) \) are responsible for controller functioning. Therefore, lesser the approximation gain value is, the lesser the peak overshoot is. The gain values of detailed coefficients \( (k_{d1}, k_{d2}, \ldots, k_{dN}) \) are only used for controlling high-frequency signals that are produced in the system due to sensor noise signals, and these gain values do not affect the output speed in ideal noise-free conditions [13, 14, 21, 22].
4. NUMERICAL SIMULATION TEST RESULTS AND DISCUSSIONS

For illustrating the performances of the WT controller, the parameters of the two identical BLDC motors are taken as 2 hp, 460 V, 60 Hz, 1750 rpm rating, and PWM sampling time of 0.5 μsec. Three different testing strategies are designed to obtain the characteristics of the electronic differential for the proposed WT EV system, where two motors are attached to the rear wheels. Investigation is carried out, in particular, under different road conditions with different speeds limits of control. A complete model of the system is numerically implemented in MATLAB/Simulink simulation software, where PID and WT control algorithms are tested in the electric drive system for their comparative performances.

4.1. Investigation Strategy, Test I

This test consists of a straight road followed by a curved road to the right in a clockwise direction at a constant speed of 60 km/hr. The speeds of the wheels change according to the command from the electronic differential during the turn. Design parameters for this case are given in Table 1.

From Figures 6 and 7, it is easily understood that the WT controller offers smooth performance compared to standard PID one. Additionally, the WT controller offers less overshoot (60.99 km/hr) and settles quickly (0.07 sec) in comparison to the PID controller’s electronic differential (63 km/hr, 0.09 sec). Therefore, it is confirmed that both motors produced smooth control with better turning performance of the EV by WT.

4.2. Investigation Strategy, Test II

This test consists of a straight road followed by a curved road to the left in a counter-clockwise direction at a constant speed of 60 km/hr. The speeds of the wheels change according to...
the command from the electronic differential during the turn. Design parameters for this case are given in Table 2.

By investigation in Test II, it is expected and confirmed from the simulation results that the WT controller (Figure 8) based electronic differential offers smoother performance compared to the standard PID controller (Figure 9). The WT-based electronic differential retains the same lower overshoot (60.99 km/hr) and settling time (0.07 sec) in comparison to the PID controller electronic differential (63 km/hr, 0.09 sec), as in Test I. This investigation test again confirms that the left and right motors produced smooth control with better turning performance of the EV by WT.

4.3. Investigation Strategy, Test III

This strategy consists of a straight road with a constant speed of 60 km/hr, followed by a 30° right turn at 30 km/hr, followed by a straight road at a constant speed of 60 km/hr. The design parameters for this case are given in Table 3.

As expected, the simulation results for Test III show that the WT controller (Figure 10) based electronic differential offers smoother performance compared to the standard PID
FIGURE 12. Transient and peak overshoot zoomed view of output response behavior of BLDC motors by the WT controller, motor 1 (top) and motor 2 (bottom).

FIGURE 13. Transient and peak overshoot zoomed view of output response behavior of BLDC motors by the PID controller, motor 1 (top) and motor 2 (bottom).

FIGURE 14. Frequency domain (Bode plot) response for electronic differential control: (a) left motor and (b) right motor.

controller (Figure 11). Further, the WT-based electronic differential retains the same lower overshoot (60.99 km/hr) and settling time (0.07 sec) in comparison to the PID controller electronic differential (63 km/hr, 0.09 sec). Again, this investigation confirms that the left and right motors produced smooth control with better turning performance of the EV by WT.

To show the effectiveness of the peak overshoot and setting time of the obtained speed response by WT, a zoomed view of transient and steady-state responses of both WT and PID controllers are shown in Figures 12 and 13.

Further, comprehensive performance indices obtained by the investigation tests are detailed in Table 4. It is clearly visible that the WT controller shows superiority by less peak overshoot, quick settling time, minimized steady-state error, and optimal root mean square error (RMSE) value than does

| Specifications                  | Test I       | Test II      | Test III     |
|--------------------------------|--------------|--------------|--------------|
|                                | PID  WT      | PID  WT      | PID  WT      |
| Peak overshoot (%)             | 1.05 1.01    | 1.05 1.01    | 1.05 1.01    |
| Settling time (sec)            | 0.09 0.068   | 0.09 0.068   | 0.09 0.068   |
| Steady-state error (km/hr)     | 0.34 0.08    | 0.34 0.08    | 0.34 0.08    |
| RMSE Left motor                | 33.28 16.11  | 33.28 16.11  | 33.28 16.11  |
| RMSE Right motor               | 33.28 16.11  | 33.28 16.11  | 33.28 16.11  |

TABLE 4. Comparative performance of the controller in time-domain parameters
the PID controller, smoothly propagating two BLDC motor-driven EVs.

Finally, both right and left BLDC motors controlled by WT are analyzed using a Bode plot for their stability for continuously smooth propagation. Figures 14(a) and 14(b) represent the magnitude response plots for left and right BLDC motors, respectively. By analyzing the frequency response curves, it is concluded that the proposed WT signals have high positive gain and phase margins at different frequency spectrums for both right and left BLDC motors, which is actually connected in the rear wheels of an electric drive, hence ensuring the stability of EV drive propagation in normal and curved roads by the proposed WT IFOC controller.

5. CONCLUSIONS

This work articulated the design of an electronic differential control for EVs utilizing a WT-based IFOC speed controller. A standard PID controller of the electronic differential was replaced by the two-level DWT. Investigations are carried out under a set of designed test strategies by varying the speed and steering angle inputs, and the obtained performances are compared between both WT and PID controllers. Numerical simulation test results provided in this article prove the effectiveness of the proposed WT electronic differential by smooth control with minimal peak overshoot and quick settling time over the PID. Finally, the WT stability in speed control of the EV is ensured by Bode plot analysis. Complete investigation test strategies confirm that the WT electronic differential is suitable for EVs for smooth propagation on curved roads.

REFERENCES

[1] Guillermo, A. M., Cristian, H. D. A., Guillermo, B., and Guillermo, G., “A neighbourhood electric vehicle with electronic differential traction control,” Proceedings of the 34th Annual Conference on. IEEE Industrial Electronics (IEEE-IECON’08), pp. 2757–2763, Orlando, FL, 10–13 November 2008.

[2] de Castro, R. P., Oliveira, H. S., Soares, J. R., Cerqueira, N. M., and Araujo, R. E., “A new FPGA based control system for electrical propulsion with electronic differential,” Proceedings of the IEEE European Conference on Power Electronics and Applications (IEEE-EPE’07), pp. 1–10, Aalborg, Denmark, 2–5 September 2007.

[3] Zhao, Y. E., Zhang, J. W., and Guan, X. Q., “Modelling and simulation of electronic differential system for an electric vehicle with two-motor-wheel drive,” Proceedings of the IEEE Intelligent Vehicles Symposium, pp. 1209–1214, Xi’an, China, 3–5 June 2009.

[4] Draou, A., “Electronic differential speed control for two in-wheels motors drive vehicle,” Proceedings of the IEEE 4th International Conference on Power Engineering and Energy Electrical Drives (IEEE-POWERENG’13), pp. 764–769, Istanbul, Turkey, 13–17 May 2013.

[5] Chunyun, F., Hoseinnezhad, R., Jazar, R., Bab-Hadiashar, A., Watkins, S. “Electronic differential design for vehicle side-slip control”, Proc. IEEE Intl. Conf. Control, Automation and Information Sciences. IEEE-ICCAI’12, Ho Chi Minh (Vietnam), pp. 306-310, 26–29 Nov. 2012.

[6] Kahveci, H., Okumus, H. I., and Ekici, M., “An electronic differential system using fuzzy logic speed controlled in-wheel brushless DC motors,” Proceedings of the IEEE 4th International Conference on Power Engineering and Energy Electrical Drives (IEEE-POWERENG’13), pp. 881–885, Istanbul, Turkey, 13–15 May 2013.

[7] Hsu, P. N., “Design of an electronic differential for a formula electric race car,” Proceedings of the IEEE International Conference on Electric Machines & Drives (IEEE-IEMDC’13), pp. 62–66, Chicago, IL, 12–13 May 2013.

[8] Saleh, S. A., and Azizur Rahman, M., “Experimental performances of the single-phase wavelet-modulated inverter,” IEEE Trans. Power Electron., Vol. 36, No. 9, pp. 2650–2661, September 2011.

[9] Saleh, S. A., “The implementation and performance evaluation of 3φ vs wavelet modulated AC-DC converters,” IEEE Trans. Power Electron., Vol. 28, No. 3, pp. 1096–1106, March 2013.

[10] Khan, M. A. S. K., and Rahman, M. A., “Implementation of a new wavelet controller for interior permanent magnet motor drives,” IEEE Trans. Ind. Appl., Vol. 44, pp. 1957–1965, 2008.

[11] Sanjeevikumar, P., Febin Daya, J. L., Blaabjerg, F., Mir-Nasiri, N., and Ertas, A. H., “Numerical implementation of wavelet and fuzzy transform IFOC for three-phase induction motor,” Eng. Sci. Technol. Int. J., DOI: 10.1016/j.jestech. 2015. 07.002, August 2015.

[12] Sanjeevikumar, P., Febin Daya, J. L., Blaabjerg, F., Wheeler, P., Oleschuk, V., Ertas, A. H., and Mir-Nasiri, N., “Wavelet-fuzzy speed indirect field oriented controller for three-phase AC motor drive—investigation and implementation,” Eng. Sci. Technol. Int. J., Vol. 19, No. 1, pp. 96–100, March 2016.

[13] Febin Daya, J. L., Subbiah, V., and Sanjeevikumar, P., “Robust speed control of an induction motor drive using wavelet-fuzzy based self-tuning multi-resolution controller,” Int. J. Computat. Intell. Syst., Vol. 6, No. 4, pp. 724–738, July 2013.

[14] Febin Daya, J. L., Subbiah, V., Iqbal, A., and Sanjeevikumar, P., “A novel wavelet-fuzzy based indirect field oriented control of induction drives,” Korean Inst. Power Electron. J. Power Electron., Vol. 13, No. 4, pp. 656–668, July 2013.

[15] Hung, Y.-C., Lin, F.-J., Hwang, J.-C., Chang, J.-K., and Ruan, K.-C., “Wavelet fuzzy neural network with asymmetric membership function controller for electric power steering system via improved differential evolution,” IEEE Trans. Power Electron., Vol. 38, No. 4, pp. 2350–2362, April 2014.

[16] Sun, C., Moura, S. J., Hu, X., Hedrick, J. K., and Sun, F., “Dynamic traffic feedback data enabled energy management in plug-in hybrid electric vehicles,” IEEE Trans. Power Electron., Vol. 23, No. 3, pp. 1075–1086, May 2015.

[17] Liu, H., Loh, P. C., and Blaabjerg, F., “Sub-module short circuit fault diagnosis in modular multilevel converter based on wavelet transform and adaptive neuro fuzzy inference system,” J. Electr.
BIograPhies

Febin J. L. Daya received his B.E. in electrical and electronics engineering from Manonmaniam Sundarnar University, India, in 2002; his M.E. in applied electronics from Anna University, India, in 2005; and his Ph.D. in information and communication from Anna University, India, in 2013. He worked with the Department of Electrical and Electronics Engineering at Sri Krishna College of Engineering and Technology, Coimbatore, India, from 2005 to 2011. Presently he is an associate professor in the School of Electrical Engineering at Vellore Institute of Technology (VIT) University, Chennai Campus, India. He has published 25 papers in international journals and conferences; he is a life member of the Indian Society of Technical Education and a member of the IEEE Society. His areas of interest include electrical drives, intelligent control and power electronics.

Padmanaban Sanjeevikumar received his B.E., M.Tech. (with distinction), and Ph.D. in electrical engineering from University of Madras (India), Pondicherry University (India), and University of Bologna (Italy), in 2002, 2006, and 2012, respectively. After completing his Ph.D., he worked as an associate professor with VIT University from August 2012 to May 2013. He joined the faculty of National Institute of Technology, Pondicherry, from July 2013 to December 2013. He was invited as a visiting fellow at the Department of Electrical Engineering, Qatar University, Qatar, from January 2014 to February 2014. He continued his research activities with Dublin Institute of Technology, Ireland, from April 2014 to November 2014. Since November 2014, he has been a project head in research and development and a consultant with Ohm Technologies, Chennai, India. He has received the most excellent research paper award of IET-SEISCON 2013. He is a senior member of the IEEE Industrial Electronics, Power Electronics, and Power and Energy Society. He has published scientific papers in the field of power electronics and drives, with particular reference to research areas of multi-phase drives, multi-level converters, ac/dc drives and application to power systems and renewable energy systems.

Frede Blaabjerg was with ABB-Scandia, Randers, Denmark, from 1987 to 1988. From 1988 to 1992, he was a Ph.D. student with Aalborg University, Aalborg, Denmark. He became an assistant professor in 1992, an associate professor in 1996, and a full professor of power electronics and drives in 1998. He has received 15 IEEE Prize Paper Awards, the IEEE PELS Distinguished Service Award in 2009, the EPE-PESC Council Award in 2010, the IEEE William E. Newell Power Electronics Award 2014, and the Villum Kann Rasmussen Research Award 2014. He was an editor-in-chief of IEEE Transactions on Power Electronics from 2006 to 2012. He has been a distinguished lecturer for the IEEE Power Electronics Society from 2005 to 2007 and for the IEEE Industry Applications Society from 2010 to 2011. He was nominated in 2014 by Thomson Reuters as one of the 250 most cited researchers in engineering in the world. His current research interests include power electronics and its applications, such as in wind turbines, photovoltaic (PV) systems, reliability, harmonics, and adjustable-speed drives.

Patrick W. Wheeler received his B.Eng. (hons.) from University of Bristol, Bristol, UK, in 1990 and his Ph.D. in electrical engineering for his work on matrix converters from the same university in 1994. In 1993, he moved to the University of Nottingham and worked as a research assistant in the Department of Electrical and Electronic Engineering. In 1996, he became a lecturer in the Power Electronics, Machines and Control Group at the University of Nottingham, Nottingham, UK. Since January 2008, he has been a full professor in the same research group and head of the department. He has published more than 400 academic publications in leading international conferences and journals. He is a senior member of the IEEE, a fellow of the IET, and a distinguished...
lecturer for the IEEE Power Electronics Society. His current research interests include power electronics for power conversion, matrix converters, multi-level/converters/multi-cellular converters for high-power/voltage applications in the electrical grid, and technologies for more-electric aircraft.

Joseph Olorunfemi Ojo, a fellow of the Institute of Electrical Engineers (FIEE), was born in Kabba, Nigeria. He received his bachelor’s and master’s degrees in electrical engineering from Ahmadu Bello University, Zaria, Nigeria, and his Ph.D. from the University of Wisconsin, Madison. He is currently a professor of electrical and computer engineering at Tennessee Technological University, Cookeville, USA. He was the chair of the Industrial Power Converter System Department of the IEEE Industry Application Society. He is also an associate editor of IEEE Transaction on Power Electronics and a member of the editorial board of the IET (UK) Journal of Power Electronics. He is the deputy editor-in-chief of IEEE Journal of Emerging and Selected Topics in Power Electronics. His current research interests span the areas of electric machine analysis and drive control, switching converter technology, and modern control applications in converter-enhanced power and distributed energy generation systems.

Ahmet H. Ertas received B.S. (with distinction) in mechanical engineering from Ataturk University, Turkey, in 1997 and his M.S. and Ph.D. in mechanical engineering from Bogazici University, Turkey, in 2004 and 2009, respectively. After completing his Ph.D., he continued his scientific research activities with Ohio University, USA from 2009 to 2011. In 2011, he joined Karabuk University as an assistant professor and worked until 2015. Since 2015, he has been promoted and is working as an associate professor with the same university. He is a member of the IEEE Society and is an editor/editorial board member of reputed journals. He has published more than 30 scientific papers in referred journals/conferences in the field of electro-mechanical engineering, with particular reference to his research areas of interest in design and analysis of structures, areas of mechanical engineering, and electrical drives.