

A simplified sensorless speed control of permanent magnet synchronous motor using model reference adaptive system

Everestus Ojionuka^{*}, Ifeanyi Chinaeke-Ogbuka^{**},
Cosmas Ogbuka^{*}, Cajethan Nwosu^{*}

A simplified sensorless speed control of permanent magnet synchronous motor (PMSM) using model reference adaptive system (MRAS) is presented. The MRAS is designed and incorporated in a complete closed loop PMSM control system fed by a three-phase inverter that utilizes a simplified hysteresis current control (HCC) to generate gating signals. Accurate rotor position, being essential in PMSM control, is estimated using MRAS rather encoders and resolvers which are explicit position sensors thereby eliminating the drawbacks of the traditional speed sensors in drive systems. The performance of this model is compared with an existing model that utilizes encoders and resolvers. Superior performance was obtained from this new model with MRAS. After initial starting transients, it is observed that the rotor speed for the model with MRAS settled to steady state at 0.10 seconds as against the model with speed sensor which attained steady state at 0.31 seconds. Torque response follows the same pattern to return to the load torque of 11Nm at steady state after starting. After speed reversal, the model with MRAS restored to steady state to track the negative speed command at 0.44 seconds. This is a superior performance compared to the model with speed sensor which settled at 0.60 seconds after speed reversal. The results have clearly shown the superiority of sensorless MRAS over traditional drive models with speed sensors. The software used for this research is MATLAB/Simulink 2017 model.

Key words: PMSM, sensorless, model reference adaptive system (MRAS), hysteresis current controller (HCC)

1 Introduction

Permanent magnet synchronous motors (PMSMs) are widely used in low and medium power applications such as computer peripheral equipment, robotics, adjustable speed drives and electric vehicles [1]. With lots of advantages, such as high torque density, small size and low maintenance cost, the permanent magnet synchronous motors (PMSMs) find wide applications at home and in industries [2,3,4]. The elimination of slip rings and field exciting coils by using permanent magnets in the rotor results in low maintenance requirement, reduced inertia and losses [5]. The reduced motor volume is due to the high field strength [6]. However, PMSM requires the ac stator current to generate constant torque and the rotor flux position to control the torque. Nevertheless, the use of explicit speed sensors such as resolvers and encoders in PMSM drives increases noise, system complexity and cost [7].

In order to overcome these shortcomings, sensorless control of motor position and speed for PMSMs has been trending in recent years proposing different methods of estimating rotor speed and position. In the low speed region, high frequency signals are injected [8,9] to extract position and speed signals. The objective is to achieve speed control at standstill and low speed regions.

The disadvantage of this method is the introduction of high frequency noise to the system. The use of state observers to estimate rotor speed and position have also been proposed in such methods as: extended kalman filters (EKF) [10,11], sliding mode observers [12,13] and unscented kalman filters [14]. The output signals in these methods are equivalent with the actual state of the system, but they present very complicated computation.

Other sensorless control schemes includes back emf method with the limitation of sensitivity to stator resistance mismatch and system noise during low speed operation [15,16], Low frequency voltage injection at low speeds and standstill with the limitation of low starting torque and generally poor dynamic performance [17], diagonally recurrent neural network (DRNN) with the limitations, in real-time motor control applications, of static mapping characteristics, the requirement for a large number of neurons and a long training time [18]. Finally, model reference adaptive system (MRAS) was used in [19, 20]. The advantage of this method is its simplicity and excellent dynamic performance.

In this work, MRAS was used for accurate speed and position sensing for PMSM drive that utilizes a simplified hysteresis current control (HCC) in the generation of gating signals for the voltage source inverter (VSI). The

^{*} Power Devices Laboratory, Department of Electrical Engineering, everestus.ojionuka.pg80560@unn.edu.ng, cosmas.ogbuka@unn.edu.ng, cajethan.nwosu@unn.edu.ng, ^{**} Department of Electronic Engineering, ifeanyi.chinaeke-ogbuka@unn.edu.ng, University of Nigeria, Nsukka

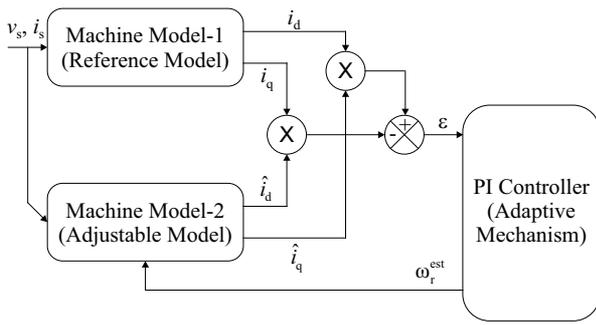


Fig. 1. Block diagram of MRAS control

emphasis is in achieving effective and accurate tracking of speed and torque. The results achieved by this method is compared with the model already presented in [21,22] under the same condition but with the use of rotor speed sensor. This new model using sensorless MRAS shows superior performance for all performance indicators examined.

2 Methodology

2.1 $d-q$ modeling of PMSM

It is convenient to design the control scheme and represent the motor model in a dq frame rotating with rotor speed for field orientation. In the PMSM, the main magnetic field is produced by permanent magnets placed on the rotor. Thus, the direct and quadrature axis voltage equations are given by [23]

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} -\omega_s L_q & R_s + \frac{dL_d}{dt} \\ R_s + \frac{dL_q}{dt} & \omega_s L_d \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{d\lambda_f}{dt} & \omega_r \lambda_f \end{bmatrix} \quad (1)$$

where, V_d and V_q are the $d-q$ axis voltages, i_d, i_q are the $d-q$ axis currents, ω_r is the rotor speed, R_s is the stator resistance, L_d and L_q are the d and q -axis inductances, λ_f is the flux due to permanent magnet.

2.2 The proposed sensorless control method

Model reference adaptive system (MRAS) is designed in order to estimate rotor speed and position. The purpose is to decrease the speed and torque fluctuations of the permanent magnet synchronous motor (PMSM) during sudden load changes. However, the model reference adaptive approach makes use of two independent machine models of different structures to estimate the same state variable (back emf, rotor flux, reactive power, current, etc) based on different sets of input variables. The error ε of the actual and estimated output is fed to the adaptation mechanism which outputs the estimated rotor

speed ω_r^{est} . This estimated speed is processed by the integrator to obtain the estimated rotor position θ_{est} . This estimated speed is used to tune the adjustable model till error ε is zero at which the estimated speed is equal to the actual speed ω_r . The schematic block diagram of MRAS with input and output signals is shown in Fig. 1.

In this MRAS control algorithm, the reference model is the PMSM itself and the adjustable model is the PMSM stator current equations in the rotating reference frame. The adaptation mechanism is a PI controller. Thus, the adjustable model equations are represented by

$$p \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r \frac{L_q}{L_d} \\ -\omega_r \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{V_d}{L_d} \\ \frac{V_q}{L_q} - \omega_r \frac{\lambda_f}{L_q} \end{bmatrix} \quad (2)$$

Since $\lambda_f = Li$, equation (2) can be represented as

$$p \begin{bmatrix} i_d + \frac{\lambda_f}{L_d} \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r \frac{L_q}{L_d} \\ -\omega_r \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d + \frac{\lambda_f}{L_d} \\ i_q \end{bmatrix} + \begin{bmatrix} \frac{V_d}{L_d} + \lambda_f \frac{R_s}{L_d^2} \\ \frac{V_q}{L_q} \end{bmatrix} \quad (3)$$

Again, we define i_d^*, i_q^*, V_d^* and V_q^*

$$\begin{aligned} i_d^* &= i_d + \frac{\lambda_f}{L_d}, & i_q^* &= i_q \\ V_d^* &= V_d + \lambda_f \frac{R_s}{L_d}, & V_q^* &= V_q. \end{aligned} \quad (4)$$

hence, substituting (4) into (3), we obtain

$$p \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r \frac{L_q}{L_d} \\ -\omega_r \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} + \begin{bmatrix} \frac{V_d^*}{L_d} \\ \frac{V_q^*}{L_q} - \omega_r \frac{\lambda_f}{L_q} \end{bmatrix} \quad (5)$$

and from (5), the state equation for the adjustable model of PMSM with speed is

$$p \begin{bmatrix} \hat{i}_d^* \\ \hat{i}_q^* \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} & \omega_r \frac{L_q}{L_d} \\ -\omega_r \frac{L_d}{L_q} & -\frac{R_s}{L_q} \end{bmatrix} \begin{bmatrix} \hat{i}_d^* \\ \hat{i}_q^* \end{bmatrix} + \begin{bmatrix} \frac{V_d^*}{L_d} \\ \frac{V_q^*}{L_q} - \omega_r \frac{\lambda_f}{L_q} \end{bmatrix} \quad (6)$$

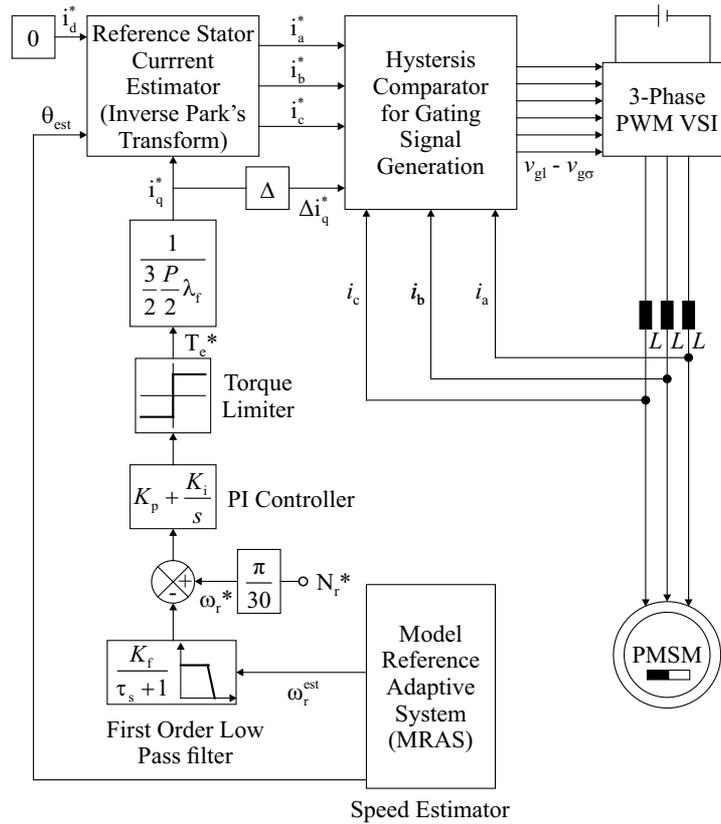


Fig. 2. Schematic diagram of the PMSM sensorless drive system with MRAS

$$\hat{i}_d^* = \hat{i}_d + \frac{\lambda_f}{L_d}, \text{ and } \hat{i}_q^* = \hat{i}_q \quad (7)$$

$$\theta_{est} = \int_0^t \omega_r^{est} dt \quad (11)$$

The Circumflex accent is used to distinguish the state variables of the adjustable model from that of the reference model. Equation (6) is the modelling equation for the model reference adaptive system, where current and voltage are the inputs to the system. In this case, the outputs of the reference model and the adjustable model are two estimates of the stator currents. The speed tuning signal actuates the rotor speed, which makes the error converge to zero. Hence, the estimated speed is given by

$$\omega_r^{est} = k_p \varepsilon + k_i \int \varepsilon dt \quad (8)$$

In $d - q$ rotating reference frame, the input to the adaptive mechanism which is a PI controller is given by

$$\varepsilon = i_d \hat{i}_q - i_q \hat{i}_d \quad (9)$$

The complete equation for the estimated rotor speed ω_r^{est} is given by equation (10). It is also known as the control law

$$\begin{aligned} \omega_r^{est} = & \int_0^t k_i \left(i_d \hat{i}_q - i_q \hat{i}_d - \frac{\lambda_f}{L_d} (i_q - \hat{i}_q) \right) dt \\ & + k_p \left(i_d \hat{i}_q - i_q \hat{i}_d - \frac{\lambda_f}{L_d} (i_q - \hat{i}_q) \right) + \omega_r^{est}(0) \end{aligned} \quad (10)$$

The i_d^* and i_q^* are used for inverse Park's transform, in addition to the estimated electrical rotor position θ_{est} obtained from the MRAS block, to produce the reference stator phase currents i_a^* , i_b^* and i_c^*

$$\begin{aligned} i_a^* &= i_q^* \cos \theta_e + i_d^* \sin \theta_e \\ i_b^* &= i_q^* \cos \left(\theta_e - \frac{2\pi}{3} \right) + i_d^* \sin \left(\theta_e - \frac{2\pi}{3} \right) \\ i_c^* &= i_q^* \cos \left(\theta_e + \frac{2\pi}{3} \right) + i_d^* \sin \left(\theta_e + \frac{2\pi}{3} \right) \end{aligned} \quad (12)$$

Hysteresis current control is accomplished by the logical comparison of the reference phase currents (i_a^* , i_b^* , i_c^*), the actual phase current of the motor (i_a , i_b , i_c) and Δi_q^* as shown below resulting in the generation of gating signals v_{g1} to v_{g6} for the firing of the inverter switches.

3 Sensorless control system for PMSM using MRAS

Control of PMSM requires speed and position information for rotor speed and torque control. The schematic diagram for the sensorless control of PMSM using MRAS

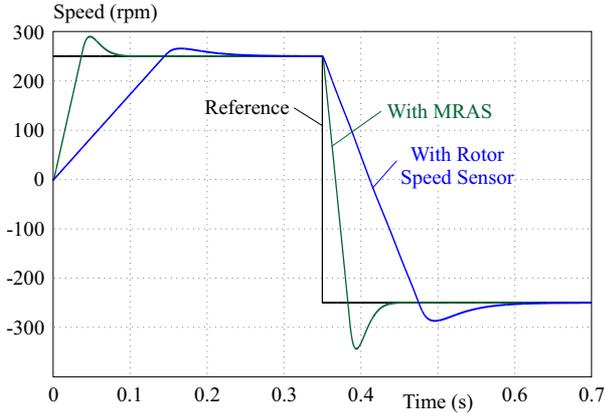


Fig. 3. Rotor reference speed, MRAS speed and speed with sensor

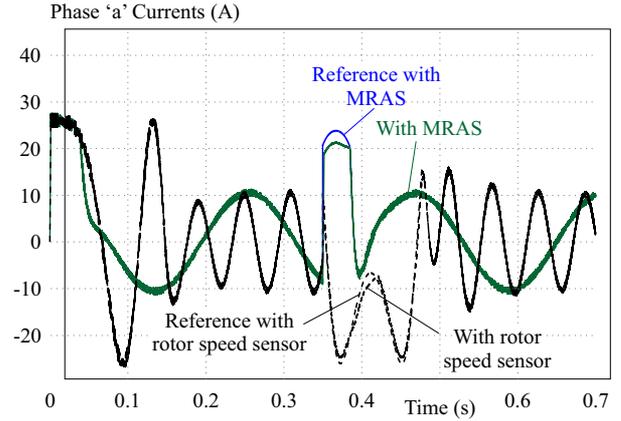


Fig. 4. Reference and actual phase a currents for MRAS and speed sensor

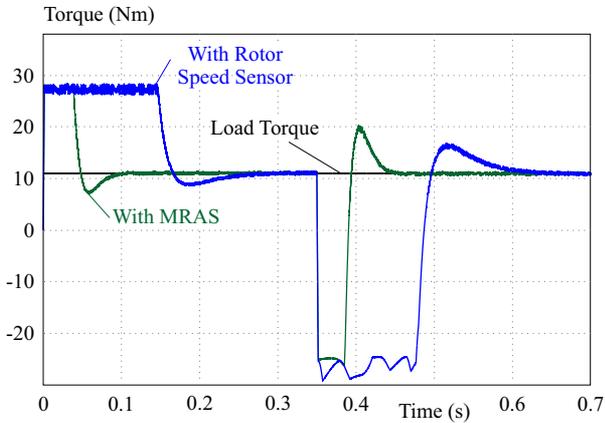


Fig. 5. Load torque, torque with MRAS and torque with speed sensor

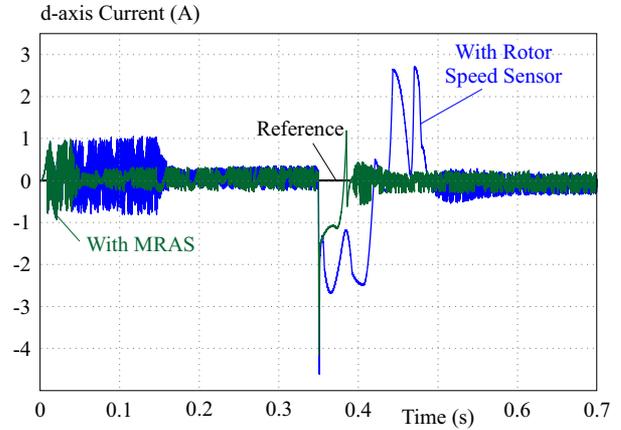


Fig. 6. d-axis current.reference, speed sensor and MRAS

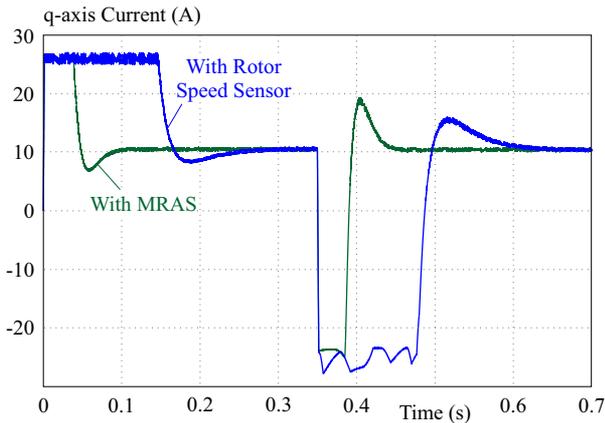


Fig. 7. q-axis current.reference, speed sensor and MRAS

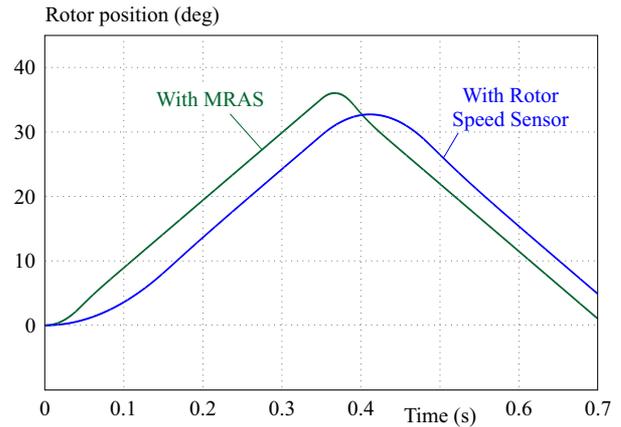


Fig. 8. Rotor position, with MRAS and speed sensor

is shown in Fig. 2. Reference variables are distinguished from the actual values by superscript *. A PI controller processes the error between the reference speed ω_r^* and the estimated speed ω_r^{est} to eliminate the steady state error in speed. The output of the PI controller is the torque reference which is restricted to an upper and a lower limit

by the torque limiter thereby producing a realistic torque reference T_e^* for comparison with the actual torque T_e . Inverse of the motor torque constant multiplies the torque reference to produce the reference quadrature axis current i_q^* . The reference direct axis current is set to zero (ie $i_d^* = 0$) as a requirement for field orientation [21,22].

Table 1. Parameters of the PMSM

Motor parameters	Symbol/Unit	Value
Rated power	Hp	4
Frequency	Hz	50
Stator resistance	R_s (Ω)	0.2
Magnetizing flux linkage	(W)	0.175
d -axis inductance	L_d (H)	0.0085
q -axis inductance	L_q (H)	0.0085
Moment of inertia	J (Kgm^2)	0.42
No of poles	P	6

4 Results and analysis

Figures 3-8 shows the drive performance of the PMSM using MRAS in comparison with the performance of an earlier model, under the same condition, but using rotor speed sensor as already reported in [21,22]. The obtained results show clear advantage of the model with sensorless MRAS over the model with rotor speed sensor. The parameters of the PMSM are shown in Appendix 1.

Comparison of rotor speed in Fig. 3 shows that the model with MRAS reached steady state at about 0.1 seconds as against 0.3 seconds for the model with rotor speed sensor. Again, after speed reversal at 0.35 seconds, the model with MRAS recovered faster from transients and continued to track the speed reference and settled to steady state at about 0.43 seconds as against 0.62 for the model with speed sensor. Figure 4 shows a combined plot of the reference and actual currents for phase a. It is observed that the actual current of both the MRAS and Speed sensor effectively tracks their individual references before, during and after speed reversal with the MRAS showing. However, in terms of motor performance, it is observed that the MRAS performed better since it recovered faster after speed reversal than the method with speed sensor. Fig. 5 shows the comparison between the torque produced by MRAS and that produced using rotor speed sensor. Again, it is observed that the MRAS torque settled and reached steady state faster at about 0.1 seconds during which the estimated torque tracks the 11Nm load torque. This is as against the torque from the model with speed sensor which attained steady state at about 0.3 seconds. Thus, the superiority of MRAS over that with speed sensor. The combined plot of the d -axis current for MRAS and Speed sensor is shown in Fig. 6. Since the d -axis current is zero in FOC and is specified as zero in the model, the d -axis current average is zero both at start and at steady state. By comparison, it is evidence that the d -axis current for the model with MRAS performs better than that of the model with speed sensor. It averages to zero both during transient and at steady state which was achieved at 0.01 second. The same superior performance of the MRAS is also seen in the q -axis current comparison shown in Fig. 7.

The comparison of the rotor positions is shown in Fig. 8. The rotor position for the MRAS, at any time instant, is ahead of the rotor position for the model with speed sensor. This account for the MRAS restoring to steady state faster than the model with speed sensor. However, the faster and smoother speed reversal seen in Fig. 3 is due to the sharp reversal of in rotor orientation as shown in Fig. 7.

5 Conclusion

A simplified sensorless speed control of PMSM using MRAS has been presented in this paper. The core methodology was to compare the performance of the sensorless control of PMSM using MRAS with the performance of an earlier model of the same systems using hardware encoders and resolvers for speed and position feedback. The complete system is based on FOC where the direct axis (d -axis) current is commanded as zero; thus, only the q -axis current state equation was used as the reference model to estimate the rotor position and speed. A simplified Hysteresis Current Control algorithm was used to generate the gating signals for inverter switching. The results show that the proposed model with MRAS performed much better than the conventional method which involves hardware speed sensors. This is proven by the superior speed and torque responses of the model with MRAS during transient and steady state in comparison with the earlier model with hardware speed sensors.

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Everestus Ojionuka (Engr) was born on 9th July 1989 in Nsukka Nigeria. He obtained his BEng Degree (Second Class Upper) in 2014 and MEng Degree in July 2019 with a Distinction. His MEng thesis is titled: Sensorless Speed control of permanent Magnet Synchronous Motor using Model Reference Adaptive System. Ahead of his doctoral research, he is currently a research team member in the Power Devices Laboratory of the Department of Electrical Engineering, University of Nigeria, Nsukka.

Ifeanyi Chinaeke-Ogbuka (Engr) was born in Nsukka Nigeria on 14th September 1989. She obtained her Bachelors of Engineering (BEng) in Electronic Engineering and Masters of Engineering (MEng) also in Electronic Engineering Department of the University of Nigeria, Nsukka. She currently serves as a Lecturer II in the same Department. Her research interests are in Electronic, Communications, Control, and Instrumentation. She is a member of the Nigerian Institution of Electrical and Electronic Engineers (NIEEE). She has published in peer-reviewed journals and presented papers in refereed conferences.

Cosmas Ogbuka (Engr, Dr) was born in Umuna Nigeria on 1st April 1981. He holds the following degrees from the Department of Electrical Engineering, University of Nigeria Nsukka, where he has attained the rank of Senior Lecturer: BEng (First Class Honors), MEng (Distinction) and PhD obtained in 2004, 2009, and 2014 respectively. His research interests include Electrical Machines, Drives and Power Electronics. He is currently an International Faculty Fellow at the Massachusetts Institute of Technology, Cambridge Massachusetts USA having recently (February 2017 to May 2017) concluded

the MIT-ETT Fellowship under MIT International Science and Technology Initiative (MISTI-AFRICA). He previously (November 2015 to April 2016) undertook a postdoctoral research visit at the Chair of Electrical Drives and Actuators (EAA) Universitaet der Bundeswehr Muenchen Germany. He is currently the Director of the Computer Communications Centre of the University of Nigeria. He is the corresponding author for this manuscript.

Cajethan Nwosu (Engr, Dr) was born 1st October 1967. He obtained the BEng, MEng, and PhD Degrees in Electrical Engineering from the University of Nigeria, Nsukka in 1994, 2004, and 2015 respectively. In 2007, he undertook a three months pre-doctoral research on Wind/Solar Hybrid Power System and Renewable Energy Resources at the University

of Technology, Delft (TU-Delft), the Netherlands. Since 2005, he has been with the Department of Electrical Engineering, University of Nigeria, Nsukka, where he is currently a Senior Lecturer. He had written two books and had published over thirty articles both in local and international journals. He is an executive member of Nigerian Institution of Electrical and Electronic Engineers (NIEEE), Nsukka chapter. He is a member of Power Electronics Society of Institution of Electrical and Electronic Engineering (PES IEEE). He is an editorial board member World Science Journal of Engineering Applications. His areas of research interest include power electronic converters, electrical drives and renewable energy technologies.
