Title	Self-Controlled PMSM Drive Employed in Light Electric Vehicle-Dynamic Strategy and Performance Optimization
Authors(s)	Sain, Chiranjit, Biswas, Pabitra Kumar, Satpathy, Priya Ranjan, Babu, Thanikanti Sudhakar, Alhelou, Hassan Haes
Publication date	2021-04-13
Publication information	Sain, Chiranjit, Pabitra Kumar Biswas, Priya Ranjan Satpathy, Thanikanti Sudhakar Babu, and Hassan Haes Alhelou. "Self-Controlled PMSM Drive Employed in Light Electric Vehicle-Dynamic Strategy and Performance Optimization." IEEE, April 13, 2021. https://doi.org/10.1109/access.2021.3072910.
Publisher	IEEE
Item record/more information	http://hdl.handle.net/10197/25332
Publisher's version (DOI)	10.1109/access.2021.3072910

IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 22, 2021, accepted April 8, 2021. Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2021.3072910

Self-Controlled PMSM Drive Employed in Light Electric Vehicle-Dynamic Strategy and Performance Optimization

CHIRANJIT SAIN[1], PABITRA KUMAR BISWAS[2], (Member, IEEE), PRIYA RANJAN SATPATHY[3], THANIKANTI SUDHAKAR BABU[4,5], (Senior Member, IEEE), AND HASSAN HAES ALHELOU[6,7], (Senior Member, IEEE)
[1]Department of Electrical Engineering, Siliguri Institute of Technology, Siliguri 734009, India
[2]Department of Electrical and Electronics Engineering, National Institute of Technology Mizoram, Aizawl 796012, India
[3]Department of Electrical Engineering, ITER, SOA Deemed to be University, Bhubaneswar 751030, India
[4]Department of Electrical and Electronics Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad 500075, India
[5]Department of Electrical and Electronics Engineering, Nisantasi University, 34398 Istanbul, Turkey
[6]School of Electrical and Electronic Engineering, University College Dublin (UCD), Dublin 4, D04 V1W8 Ireland
[7]Department of Electrical Power Engineering, Faculty of Mechanical and Electrical Engineering, Tishreen University, Lattakia 2230, Syria

Corresponding authors: Hassan Haes Alhelou (alhelou@ieee.org) and Thanikanti Sudhakar Babu (sudhakarbabu66@gmail.com)

The work of Hassan Haes Alhelou was supported in part by the Science Foundation Ireland (SFI) through the SFI Strategic Partnership Programme under Grant SFI/15/SPP/ E3125, and in part by the University College Dublin (UCD) Energy Institute.

ABSTRACT This proposed work demonstrates the illustration of dynamic performance intensification of a Permanent Magnet Synchronous Motor (PMSM) employed by a PWM controlled inverter which synchronizes with the rotor movement intimation. PMSM are widely hired in electric vehicles since it possesses better dynamic response, improved torque-speed property, and reduced noise, energy-efficient and power factor in comparison with traditional motors. In the present work, it is observed that by few modifications of the position control strategy as good as sinusoidal stator currents response generates less torque ripples. The mathematical model for PMSM is derived from park's transformation. Further, a maiden attempt is taken to introduce the performance indicator 'sensor angle' to estimate the rotor position in this strategy. From the established model, the various dynamic behavior of the drive system is determined analytically without and under various load disturbances. Additionally, a particle swarm optimization (PSO) technique is adopted to optimize the performance of the proposed dynamic strategy. An efficient speed control strategy by the variation of DC bus voltage is achieved which is equivalent to the armature voltage control of the conventional dc machine. Further, efficient and simple control circuitry of the voltage source inverter (VSI) is obtained in this strategy. To verify the efficacy of the proposed algorithm, necessary tests are carried out in a real-time setup. Therefore, an improved control strategy obtained from the simulation and an experimental approach meets the dynamic behavior employed in light weight electric vehicles.

INDEX TERMS Dynamic response, light vehicle, permanent magnet synchronous motor, rotor position, pulse width modulation (PWM), speed control.

I. INTRODUCTION

Since the progress of permanent magnet materials, modern power electronics and the sophisticated control technique including semiconductor fabrication technology PMSM Motors are significantly appointed in different industrial, commercial and indifferent domestic applications. Light electric vehicles are currently designed to gain lower automobile emissions. The electric motors are used in electric vehicles require better torque-speed characteristics to obtain higher operating range and improved efficiency. Generally, the characteristics of flux density distribution in the air gap and the back emf produced in the armature winding supplied by permanent magnets exhibit sinusoidal characteristics [1], [2].

The typical speed control procedures of this kind of machine could be incorporated in a method equivalent to a traditional DC machine-either by the variation DC link

The associate editor coordinating the review of this manuscript and approving it for publication was Ramazan Bayindir.

voltage/DC bus voltage or by modifying the analogous brush assembly through a variation in the sensor position on the rotor in accordance with the rotor frame identified by the proposed parameter, sang, in in this proposed concept. The function of the mechanical commutator, here is performed by the typical 3-phase VSI which is triggered in coordination with the position information. Consequently, the frequency of the currents and/or voltages in each armature phase of the PMSM is dictated by the machine speed rather than the opposite, which generally occurs in a conventional synchronous machine.

This is the true essence of, self-control, or, self-synchronous, operation whereby the rotor position dictates the commutation of devices in the armature and hence the frequency of voltage or current in the armature [3], [4].

In this proposed work an investigation on the dynamic strategy is established for the proposed PMSM while the armature is operated by a three-phase bridge inverter. In this strategy, a multi-phase inverter is controlled in synchronism with the rotor movement. Pulse width modulation is employed to adjust the power delivered to the load through the provision of a switching period of the devices [5], [6]. The total time period for the power delivery to the load computes the voltage across the load for a VSI. The inverter is designed to be operated from an adjustable rectifier source Vdc gained by the incorporation of a frond-end converter can be adjusted to introduce the speed control effectively, in the similar strategy as voltage control performed in a separately excited machine. In this proposed concept different dynamic behaviour like interaction torque, electrical speed, direct and quadrature axis currents, phase voltage and current, position information of the rotor under various operating conditions are determined analytically to reduce the ripples, noise and obtain the simple and economic control circuit [7], [8]. After determining all the performance indices of the drive system by simulation studies proposed concept is implemented in a real-time experimental set up for the validation. An updated PSO technique has been introduced to optimize the performance the PMSM drive through a tuning of the sensor angle based control algorithm. In a light electric vehicle while PMSM was employed through digital PWM, the input current of the motor needs to be controlled in order to limit its stator current due to the load applied. This could be done by sensing the current input to the motor and reducing the current to a value lesser than a predefined limit [9], [10]. Overall cost and cleanliness of the environment is a major issue in an automotive application. By designing the inverter control circuitry with few modifications of the position sensor and controlling the inverter dc-link voltage smooth and economic speed control is achieved which is advantageous.

In this proposed work an improved dynamic strategy on a PMSM drive is executed and optimized to illustrate the better dynamic and steady-state performance characteristics [11], [12]. While appraising the above discussion the main contributions are listed in the following way:

- An improved dynamic strategy of a self-controlled PMSM machine has been established under various operating conditions and an effective speed control strategy equivalent to the traditional dc machine was introduced.
- A newly adopted mechanism through the displacement in the field and armature mmf space vector can be examined to estimate rotor movement intimation in this strategy.
- A reformed PSO algorithm was employed for tuning the proposed control strategy without the optimization of the current and speed controller parameters which improve the dynamic behavior of the PMSM drive and all the other parameters of the machine are unaffected.
- Further, an elementary as well as economic control circuitry of the inverter was obtained to estimate the rotor position and finally an improved nature of the armature current was established to ensure better electromagnetic torque as desired in a light electric vehicle.

The other sections of the carried-out work are organized as follows: The analysis and design of PMSM are described in Section II, detailed discussion on sensor angle and rotor position control are given in Section III, Simulation and experimental study of proposed work are detailed in Sections IV and V respectively. Finally conclusion and outcome of the work are presented in Section VI.

II. PERMANENT MAGNET SYNCHRONOUS MOTOR DRIVE-DYNAMIC ANALYSIS

To determine the dynamic behaviour of a PMSM drive system under different operating conditions in an open-loop manner the main components like power electronic inverter, reference frame theory, machine dynamics (transient and steady-state) are incorporated. The proposed dynamic model of the drive system is carried out by representing the modelling of PWM controlled voltage source inverter in different switching conditions, mathematical analysis of parks transformation and the dynamic behaviour of PMSM machine in different operating conditions and the proposed control strategy. This proposed model of PMSM can be obtained by the mechanism of PWM controlled inverter conducted in 180^{deg} conduction. To obtain the smooth voltage waveform, sinusoidal PWM strategy is adopted in the proposed inverter circuitry to maintain the output voltage. The information of rotor position is observed by the incorporation of absolute position encoder and this signal is forwarded to the control circuitry of the inverter section [13]. This inverter controller section employs this typical information which in turn produces the switching signals for the inverter circuitry. Fig. 1 depicts the proposed scheme of the drive system.

$$V_{an} + V_{bn} + V_{cn} = 0 \tag{1}$$

$$V_{no} = \frac{1}{3}\left(V_{ao} + V_{bo} + V_{co}\right) \tag{2}$$

$$\begin{aligned} V_{no} &= \frac{1}{3}\left(V_{ao} + V_{bo} + V_{co}\right) \\ &= \frac{1}{3}\left(\frac{1}{2}V_{dc} - \frac{1}{2}V_{dc} - \frac{1}{2}V_{dc}\right) = -\frac{1}{6}V_{dc} \end{aligned} \tag{3}$$

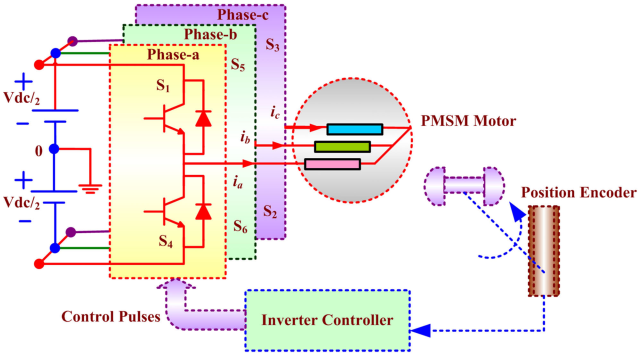


FIGURE 1. **Simplified layout diagram of a 3-phase bridge VSI fed PMSM drive.**

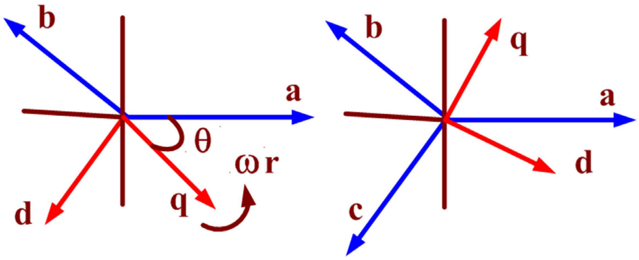


FIGURE 2. **Positions of d and q-axes with rotor position when two switching 612 and 123 are ON.**

As per the convention of the scheme, one switch from the upper leg and two switches from the lower leg are simultaneously conducting at some particular instant [14], [15]. Therefore the time gap between the switching modules of the same leg of the inverter is assumed to zero. For the proposed PWM controlled VSI the possible switching combinations are represented as 612, 123, 234, 345, 456 and 561. Hence, for different switching combinations the pole voltages of different legs and with reference to the DC link mid-point, 0, is represented in terms of DC link voltage of the proposed VSI [16]. The positions of d and q-axes with rotor position when two switching 612 and 123 are ON are shown in Fig. 2.

$$V_{an} = V_{ao} + V_{no} = \frac{2}{3}V_{dc} \tag{4}$$

$$V_{bn} = V_{bo} + V_{no} = -\frac{1}{3}V_{dc} \tag{5}$$

Therefore, by using the different switching combinations phase to neutral voltages can be determined in terms of DC link voltage of the proposed VSI. The strategy for the harmonics control and adjustment of the fundamental elements can be accomplished through a change in the span of the applied input voltage. It is identified by changing the pulse width to gate signals of the PWM operated inverter [3], [17], [18]. The modelling and dynamics of Permanent Magnet Synchronous Machine are established using parks transformation theory or d-q axis frame theory. Therefore all the mathematical equations are arranged to represent the model.

$$f_{dqo} = K_S f_{abc} \tag{6}$$

$$\begin{bmatrix} Vd \\ Vq \\ V0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} cos\theta_r & cos(\theta_r - 2\pi/3) & cos(\theta_r + 2\pi/3) \\ -sin\theta_r & -sin(\theta_r - 2\pi/3) & -sin(\theta_r + 2\pi/3) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} Van \\ Vbn \\ Vcn \end{bmatrix} \tag{7}$$

$$\theta_r = \int_0^t \omega_r(t) + \theta_r(0) \tag{8}$$

$$v^r_{qs} = r_s i^r_{qs} + \omega_r \psi^r_{ds} + p\psi^r_{qs} \tag{9}$$

$$v^r_{qs} = (r_s + pL_q) i^r_{qs} + \omega_r L d^{i^r} ds + \omega_r \psi'^r_0 \tag{10}$$

$$v^r_{ds} = r_s i^r_{ds} - \omega_r \psi^r_{qs} + p\psi^r_{qs} i^r_{ds} \tag{11}$$

$$T_{em} = \frac{3}{2}\frac{P}{2}\left(\psi^r_{ds} i^r_{qs} - \psi^r_{qs} i^r_{ds}\right) \tag{12}$$

While comparing the proposed control strategy equivalent to the traditional DC commutator machine, the developed electromagnetic torque as a function of sensor angle and dc link current, can be proposed as

$$T_e = \left(\frac{p}{2}\right) 1.655\psi_0 cos\left(sang\right) i_{link} \tag{13}$$

Eq. 13 can be used to compute the magnitude of electromagnetic torque as well as mechanical power developed in a self-controlled PMSM machine. Moreover, Eq. 13 clearly illustrates that the torque developed can be precisely controlled through the variation in sensor angle in this proposed strategy.

III. CONCEPT OF SENSOR ANGLE AND ROTOR POSITION CONTROL

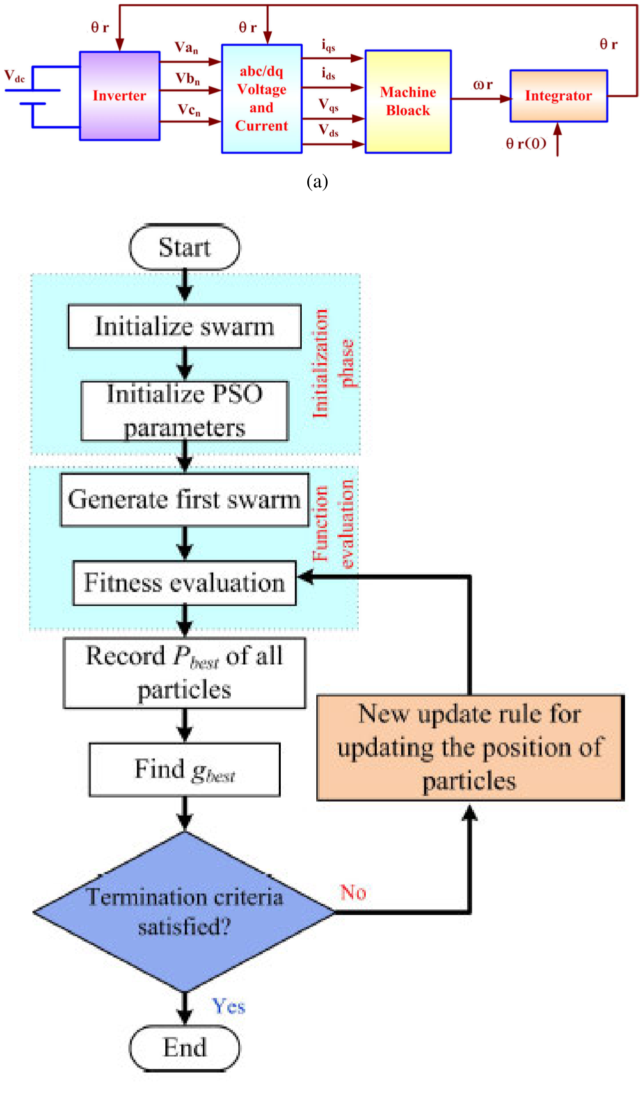
The rotor position encoder system works in synchronism as per the conduction sequence of the inverter switches. While investigating the typical model it is realized that the proper identification of a position encoder system with the corresponding inverter switching combinations provides a space angle during the rotation of the machine. The concept of sensor position can be described by a, phase displacement, variable categorized as, sang, which can be analyzed to be zero when the permanent magnet field MMF space vector (mean value taken on every 60° instant considering a specific sequence of three inverter devices are on as per 180° mode of operation) acts in space quadrature with the corresponding stator voltage trajectory [19]. It is anticipated that due to the rotation of rotor and inverter switching combinations average phase displacement for various sensor lead angles are different. Therefore the nature of electromagnetic torque profiles would be different with the corresponding sensor lead angle variation. Hence, the variation of, sang, may be an effective tool for achieving speed control. The effect of changing the sensor lead angle is hereby observed to be similar to that of varying the brush position in a conventional DC motor with the mechanical commutator and brush assembly. Hence, by the variation of identical brush arrangement through a variation in the sensor position on the rotor with respect to the rotor frame, speed and position control can be achieved in this strategy. In this proposed work different dynamic strategy i.e. speed, torque, phase voltage, d-q axis current, rotor movement are examined through the variation in sensor angle with rapid load disturbances. It is observed that due to variation of sensor lead angle of 30° leading, with the inclusion of load torque the nature of armature current response is more acceptable, establishing sinusoid characteristics [20].

IV. SIMULATION RESULTS AND DISCUSSION

To determine the different performance characteristics of a PMSM drive, mathematical modelling and dynamic simulation is carried out using flowchart depicted in Fig. 3(a). As bio-inspired algorithms are widely used in recent years than conventional techniques due to conventional algorithms most of researchers are focused to implement those algorithms for their specific applications. Thereby an array of algorithms have been introduced for various applications like design and modelling of fuel cell, solar [21], [22], maximum power extraction of power from solar PV [23], [24], load frequency control of multi interconnected renewable energy resources [25]. With this motivation authors used particle swarm optimization algorithm for enhancing performance of light electric vehicle.

An updated PSO algorithm was introduced to optimize the proposed control strategy. As the PSO is one of most widely used optimization technique to solve various multi dimensional problems and it has been successfully applied in various fields of study [26], [27]. Moreover in comparison with the traditional PSO an updated strategy based on normal distribution is applied. Further the mechanism based on velocity mechanism is eliminated. The necessary flow chart diagram for the implementation of an updated PSO is depicted in Fig. 3(b). Since this methodology seizes in priority of the particle population and eliminates few necessary co-efficient values of social and velocity criteria. Further, this algorithm was applied since optimal behavior of the drive was achieved due to the tuning of the proposed performance indicator i.e. sensor angle. For a given DC-link voltage inverter generates three-phase voltages which are converted into equivalent two-phase quantities through the park's transformation. Therefore, machine block used to receive d-q axis signals and through rotation, it gives as electrical speed and position information. Fig. 4 to Fig. 8 shows the nature of responses of net developed torque, speed, particular phase voltage and corresponding phase current, direct and quadrature axis currents, rotor position at various DC bus voltages of VSI with an adjustment of front end converter.

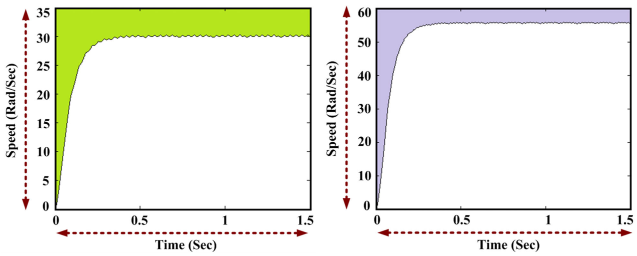
In the next case i.e. when simulated voltage is equal to 96 V (double of the previous case) is employed at DC bus of the VSI of PMSM drive; with all other conditions remain unaltered, is compared with previous one it is found that speed obtained as in Fig. 4 in this case at steady state is higher with increased input voltage [28]. Therefore, it is concluded that by the variation the DC link/bus voltage of inverter speed control can be achieved which is identical to separately excited DC machine armature voltage control.



(a)

(b)

FIGURE 3. (a) Typical flowchart for dynamic simulation of a PMSM drive, (b) Flow chart for updated PSO algorithm.

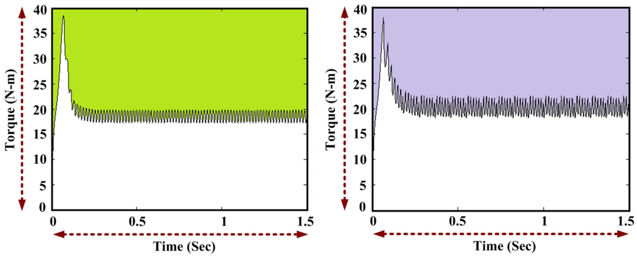


(a)

(b)

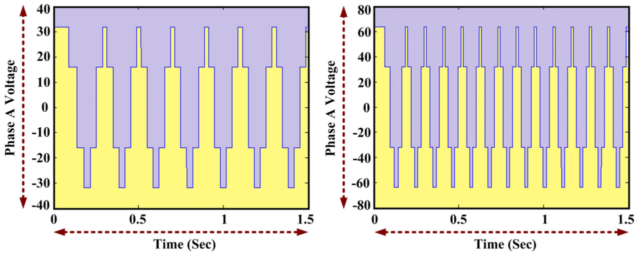
FIGURE 4. Speed versus time nature (a) when applied voltage is 48 V with T_l =0, (b) when applied voltage is 96 V with T_l =0.

The average torque and torque ripples depicted in Fig. 5 in the second case (when 96 V is applied) are also higher because of increased input voltage and increased final steady-state speed. The back-to-back torque ripple in terms of percentage of the average torque is higher here as the armature phase



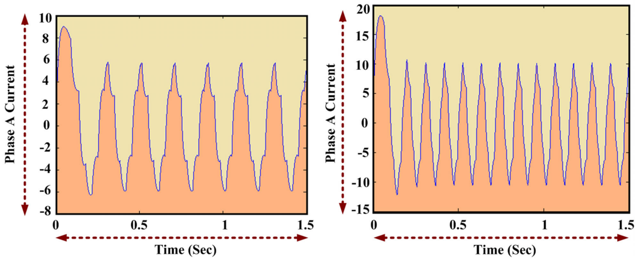
(a) (b)

FIGURE 5. Dynamic behavior of electromagnetic torque (a) when applied voltage is 48 V with T_l =0, (b) when applied voltage is 96 V with T_l =0.



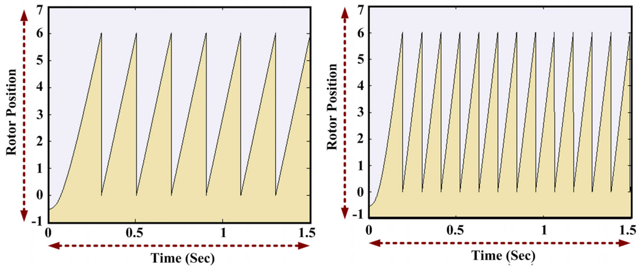
(a) (b)

FIGURE 6. Dynamic response of Phase A voltage (a) when applied voltage is 48V with T_l =0, $fn = 0.45\ Nm - sec$, (b) when applied voltage is 96 V with T_l =0, $fn = 0.45\ Nm - sec$.



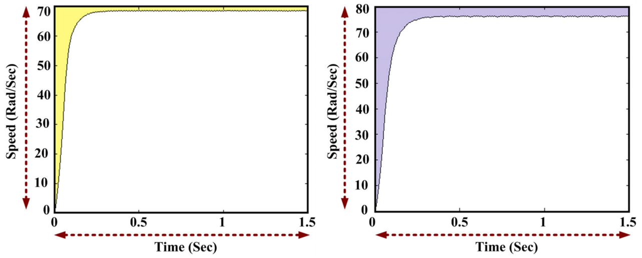
(a) (b)

FIGURE 7. Dynamic current response (a) when applied voltage is 48 V with T_l =0, (b) when applied voltage is 96 V with T_l =0.



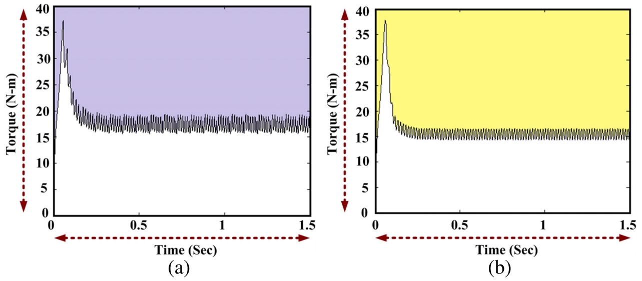
(a) (b)

FIGURE 8. Rotor movement information curve (a) when applied voltage is 48V with T_l =0, $fn = 0.45\ Nm - sec$, (b) when applied voltage is 96 V with T_l =0, $fn = 0.45\ Nm - sec$.



(a) (b)

FIGURE 9. Speed versus time response (a) 'sang'=0^{deg}, T_l =5 $N - m$, without optimization (b) 'san'=-30^{deg}, T_l =5 $N - m$, with optimization.



(a) (b)

FIGURE 10. Torque versus time response (a) 'sang'=0^{deg}, T_l =5 $N - m$, without optimization (b) 'sang'=-30^{deg}, T_l =5 $N - m$, with optimization.

current wave shape does not change much from the previous case. The particular phase voltage response in Fig. 6 appears a six stepped voltage waveform in accordance with the 2-level VSI controlling under 180^{deg} conduction. The corresponding phase current Fig. 7 and frequency of this waveforms are observed to gently increases from starting so that speed slowly builds up and frequency of voltage/current is directly locked with rotor speed because of self-synchronous operation. The amplitude of phase voltage and phase current is also higher than the previous case. The magnitude of the frequency of the voltage or current is higher as the speed is getting increased. The rotor movement intimation as depicted in Fig. 8 is observed to changes dynamically as the frequency is slowly rising; since the drive motor is supposed to acquire with the new position intimation. In this control strategy, several dynamic strategies i.e. interaction torque, electrical speed, stator current, corresponding phase voltages are analyzed and compared through the proposed updated PSO algorithm having load disturbances. The dynamic behaviour of the drive system under sensor angle based control strategy is depicted from Fig. 9 to Fig. 12 respectively. It can be observed that during the variation of sensor lead angle from 0° to −30° tuned through PSO, having load disturbances the nature of armature phase current response is improved, establishing pure sinusoid characteristics. In Fig. 9 - Fig. 10 due to this proposed optimization technique, ripples component in the speed and torque was improved. Additionally, the torque pulsations even with the load disturbances and tuned through sensor angle exhibits better dynamic response. The effect of changing the sensor lead angle is hereby observed to be identical by the variation of brush position in a separately excited DC machine having mechanical commutator and brush assembly. Hence it is also an effective kind of speed control strategy that can be applied for economic operation of the drive system. This topology can be implemented by adjusting the rotor position encoder system.

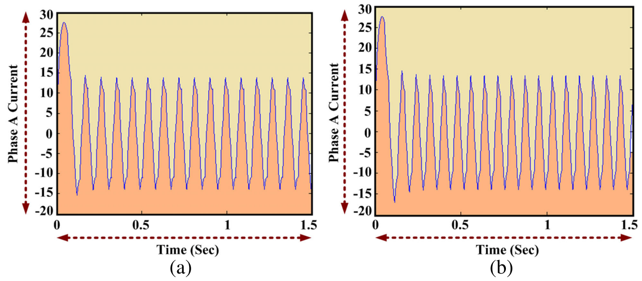


FIGURE 11. Phase A current versus time response (a) 'sang'=0^{deg}, T_l =5 $N-m$, without optimization (b) 'sang'=-30^{deg}, T_l =5 $N-m$, with optimization.

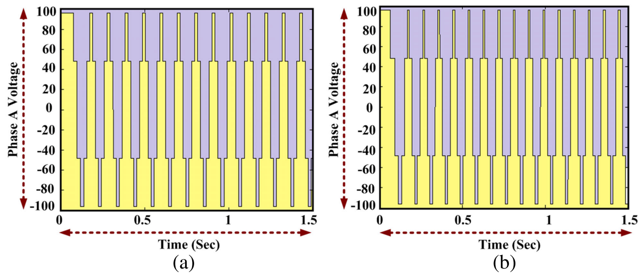


FIGURE 12. Phase voltage versus time response (a) 'sang'=0^{deg}, T_l =5 $N-m$, (b) 'sang'=-30^{deg}, T_l =5 $N-m$.

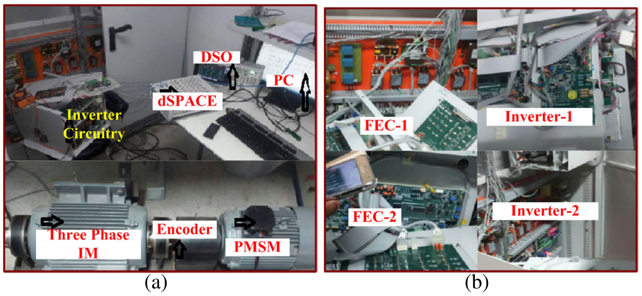


FIGURE 13. Test bench (a) Complete experimental test bench, (b) Internal circuitry of FEC and inverter control panel.

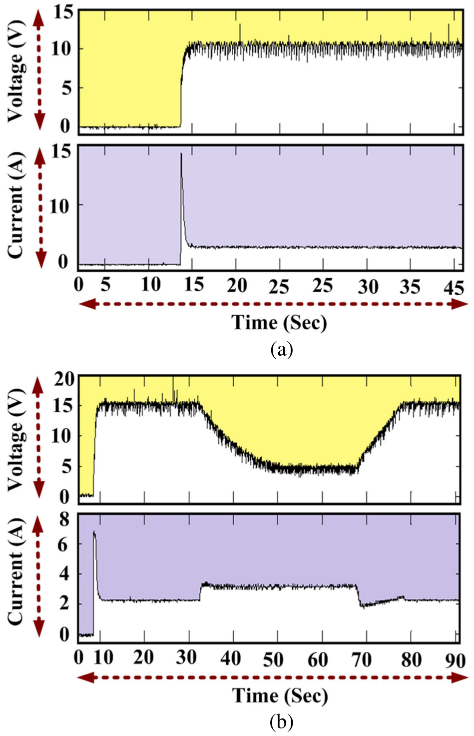


FIGURE 14. Results (a) DC link voltage and current on no-load operation, (b) Variation of DC link voltage and current for on-load operation.

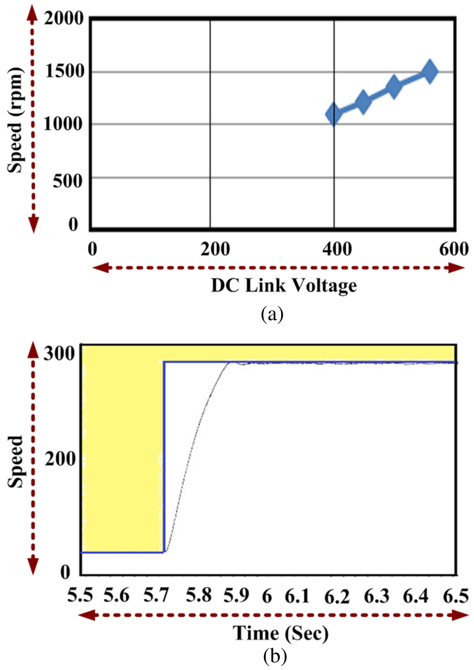


FIGURE 15. Results (a) Variation of Speed as a function of DC link voltage in real-time set up, (b) Electrical speed versus time response in real-time set up.

V. EXPERIMENTAL RESULTS AND DISCUSSION

To illustrate the efficacy of the proposed scheme, performance of the proposed PMSM drive system is observed and verified in a real-time experimental set up using d-SPACE control desk. In this experimental setup, PMSM motor is mechanically coupled with a cage-type induction motor which acts as a load on the PMSM. The present system mainly consists of Motor-Generator set (Induction motor coupled with PMSM), two front end converters (FEC-1 and FEC-2), Inverter-1 for induction motor control and inverter-2 for PMSM control. Front end converter which boosts and regulates the DC bus. The inverter takes input from the DC bus. Fig. 13(a) depicts the setup used for experimental work. The proposed algorithm of the drive system simulated in MATLAB/SIMULINK is interfaced through d-SPACE hardware for implementing the real-time validation. To achieve the desired performance of the drive system digital PWM technique is implemented for such sophisticated control with lesser ripples and smoother operation. All the detailed internal circuitry of front end converters and inverters are depicted in Fig. 13(b). Here FEC-1 and Inverter-1 are connected with Induction motor and FEC-2, Inverter-2 is connected with

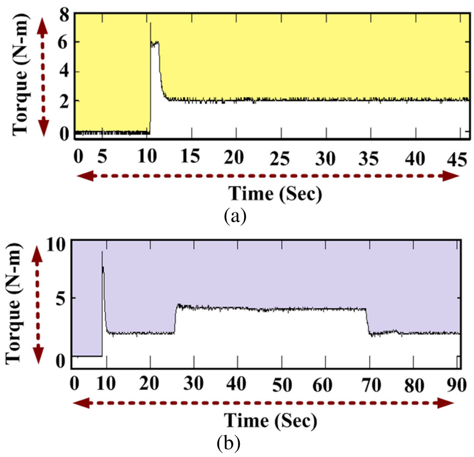


FIGURE 16. Results (a) Electromagnetic torque versus time response at no-load operation in real-time set up, (b) Electromagnetic torque versus time response at loaded condition in real-time set up.

PMSM motor panel. To validate the drive performance in real-time set-up, Fig. 14(a), 14(b) depicts the variation of DC link voltage and current on load variation, respectively. Therefore it is observed that with the load variation distortion is quite larger compared to no-load condition. Similar behaviour of the drive system is monitored in simulation studies. In the real-time, speed control of the drive system is achieved by varying the DC link voltage by implementing the proposed algorithm more smoothly as shown in Fig. 15(a). Electrical speed versus time response in real-time set up is depicted in Fig. 15(b). The speed control technique in this manner signifies the same method of armature voltage control in a separately excited DC machine. Fig. 16(a), 16(b) depicts the electromagnetic torque profile of the PMSM drive system operating under no-load and on-load conditions, respectively. It is observed that by implementing the inverter control algorithm, position sensor settings and by machine parameter variation better torque profile is obtained with lesser ripples which are the outcome of to the simulation result. Further by the introduction of the updated PSO, torque pulsations are lesser which reduces the noise and improves its steady-state performance in a multi-quadrant operation. Hence it is observed that rotor position is controlled precisely due to the variation of frequency in proposed concept. Variation of rotor position information is depicted in Fig. 17 in real time set-up which is analogous in a repetitive manner, the drive motor is supposed to adapt with the new position information. The armature current response due to this dynamic strategy was illustrated in Fig. 18 exhibits sinusoid in nature. Moreover a sudden variation in the load disturbances affects the magnitude of current at certain point; however a stable behavior was achieved finally to meet the steady-state torque. To estimate the speed various samples are taken in a flexible operating region and depicted in Fig. 19. Since it indicates that no further deviation was achieved in comparison with the traditional technique and shows better accuracy. Further, to exhibit the dynamic behavior torque-speed curve was established in Fig. 20. It is emphasized that nearly at 950 rpm magnitude of torque was maximum and gradually it decreases due to the increment in speed at various intervals. Finally, a satisfactory dynamic behavior of a PMSM drive was carried out which meets the requirement in light weight electric vehicles.

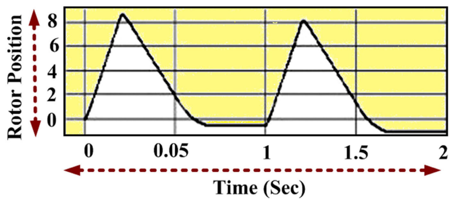


FIGURE 17. Rotor position versus time response in real-time set up.

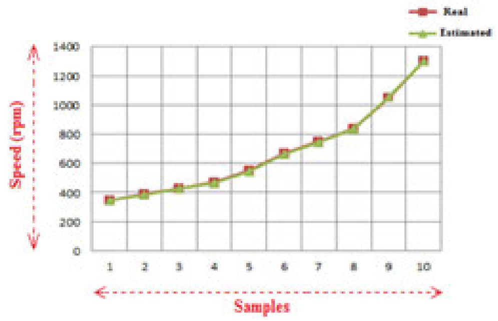


FIGURE 18. Speed estimation at various samples.

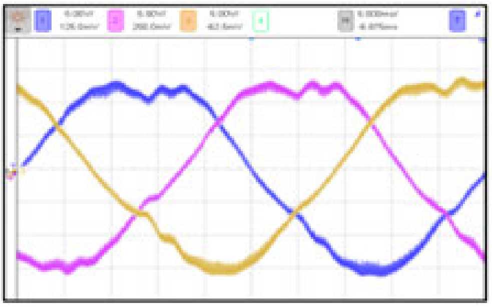


FIGURE 19. Armature current response.

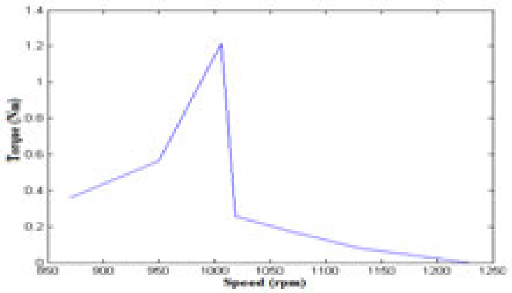


FIGURE 20. Torque-speed characteristics.

VI. CONCLUSION

In this article the dynamic performance enhancement of a PWM controlled updated PSO optimized PMSM drive under different control strategies are described and compared in a real-time experimental platform. This improved and efficient dynamic model of the drive system can evaluate dynamic as well as steady-state behaviour under different operating conditions. Effects of changes done for different DC link voltages, different sensor positions and different loads can be easily investigated with this model. It has been found that for a leading sensor position of 30o, the armature currents of the machine of the particular PMSM are near sinusoidal. These near-sinusoidal armature currents interact with the sinusoidally distributed permanent magnet flux to yield an electromagnetic torque with less torque ripples. Further, through updated PSO optimized strategy current ripples and torque pulsations are reduced in a significant manner. Therefore, an extremely simple control circuit of the inverter is achieved which is economical and advantageous in a light electric vehicle application. Hence the outcome of proposed work is to apply and analyze the control strategies of a PMSM drive in automotive industries for the benefit of society and mankind.

ACKNOWLEDGMENT

The opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Science Foundation Ireland. For the purpose of Open Access the author has applied a CC BY public copyright license to any author accepted manuscript version arising from this submission.

REFERENCES

[1] R. Krishnan, *Electric Motor Drives: Modeling, Analysis, and Control*. London, U.K.: Pearson, 2001.

[2] K. Bimal, *Modern Power Electronics and AC Drives*. Upper Saddle River, NJ, USA: Prentice-Hall, 2001.

[3] X. Yuan, S. Zhang, and C. Zhang, "Enhanced robust deadbeat predictive current control for PMSM drives," *IEEE Access*, vol. 7, pp. 148218–148230, 2019.

[4] C. Sain, A. Banerjee, and P. K. Biswas, "Modelling and comparative dynamic analysis due to demagnetization of a torque controlled permanent magnet synchronous motor drive for energy-efficient electric vehicle," *ISA Trans.*, vol. 97, pp. 384–400, Feb. 2020.

[5] J. J. Justo, F. Mwasilu, E.-K. Kim, J. Kim, H. H. Choi, and J.-W. Jung, "Fuzzy model predictive direct torque control of IPMSMs for electric vehicle applications," *IEEE/ASME Trans. Mechatronics*, vol. 22, no. 4, pp. 1542–1553, Aug. 2017.

[6] P. H. Nguyen, E. Hoang, and M. Gabsi, "Performance synthesis of permanent-magnet synchronous machines during the driving cycle of a hybrid electric vehicle," *IEEE Trans. Veh. Technol.*, vol. 60, no. 5, pp. 1991–1998, Jun. 2011.

[7] C. Sain, A. Banerjee, P. K. Biswas, T. S. Babu, and T. Dragicevic, "Updated PSO optimised fuzzy-PI controlled buck type multi-phase inverter-based PMSM drive with an over-current protection scheme," *IET Electr. Power Appl.*, vol. 14, no. 12, pp. 2331–2339, Dec. 2020.

[8] W. Wang, Y. Feng, Y. Shi, M. Cheng, W. Hua, and Z. Wang, "Fault-tolerant control of primary permanent-magnet linear motors with single phase current sensor for subway applications," *IEEE Trans. Power Electron.*, vol. 34, no. 11, pp. 10546–10556, Nov. 2019.

[9] F. Toso, D. D. Ru, P. Alotto, and S. Bolognani, "A moving horizon estimator for the speed and rotor position of a sensorless PMSM drive," *IEEE Trans. Power Electron.*, vol. 34, no. 1, pp. 580–587, Jan. 2019.

[10] X. Zhang, L. Zhang, and Y. Zhang, "Model predictive current control for PMSM drives with parameter robustness improvement," *IEEE Trans. Power Electron.*, vol. 34, no. 2, pp. 1645–1657, Feb. 2019.

[11] X. Zeng, L. Quan, X. Zhu, L. Xu, and F. Liu, "Investigation of an asymmetrical rotor hybrid permanent magnet motor for approaching maximum output torque," *IEEE Trans. Appl. Supercond.*, vol. 29, no. 2, Mar. 2019, Art. no. 0602704.

[12] Y. Fang and T. Zhang, "Sound quality of the acoustic noise radiated by PWM-fed electric powertrain," *IEEE Trans. Ind. Electron.*, vol. 65, no. 6, pp. 4534–4541, Jun. 2018.

[13] R. M. Pindoriya, G. Gautam, and B. S. Rajpurohit, "A novel application of pseudorandom-based technique for acoustic noise and vibration reduction of PMSM drive," *IEEE Trans. Ind. Appl.*, vol. 56, no. 5, pp. 5511–5522, Sep. 2020.

[14] C. Xu, Z. Han, and S. Lu, "Deadbeat predictive current control for permanent magnet synchronous machines with closed-form error compensation," *IEEE Trans. Power Electron.*, vol. 35, no. 5, pp. 5018–5030, May 2020.

[15] Y. Miyama, M. Hazeyama, S. Hanioka, N. Watanabe, A. Daikoku, and M. Inoue, "PWM carrier harmonic iron loss reduction technique of permanent-magnet motors for electric vehicles," *IEEE Trans. Ind. Appl.*, vol. 52, no. 4, pp. 2865–2871, Jul. 2016.

[16] Z. Shen, D. Jiang, L. Zhu, Y. Xu, T. Zou, Z. Liu, and R. Qu, "A novel zero-sequence current elimination PWM scheme for an open-winding PMSM with common DC bus," *IEEE Trans. Power Electron.*, vol. 34, no. 12, pp. 12476–12490, Dec. 2019.

[17] J. Zhao, L. Zheng, S. Wang, and M. Hua, "Research on deadbeat current prediction vector control system of axial flux permanent magnet synchronous motor for electric bus based on efficiency optimal torque distribution method," *IEEE Access*, vol. 7, pp. 128384–128393, 2019.

[18] L. Yan and X. Song, "Design and implementation of Luenberger model-based predictive torque control of induction machine for robustness improvement," *IEEE Trans. Power Electron.*, vol. 35, no. 3, pp. 2257–2262, Mar. 2020.

[19] R. S. Dastjerdi, M. A. Abbasian, H. Saghafi, and M. H. Vafaie, "Performance improvement of permanent-magnet synchronous motor using a new deadbeat-direct current controller," *IEEE Trans. Power Electron.*, vol. 34, no. 4, pp. 3530–3543, Apr. 2019.

[20] P. Gao, G. Zhang, H. Ouyang, and L. Mei, "A sliding mode control with nonlinear fractional order PID sliding surface for the speed operation of surface-mounted PMSM drives based on an extended state observer," *Math. Problems Eng.*, vol. 2019, Sep. 2019, Art. no. 7130232.

[21] D. Yousri, H. M. Hasanien, and A. Fathy, "Parameters identification of solid oxide fuel cell for static and dynamic simulation using comprehensive learning dynamic multi-swarm marine predators algorithm," *Energy Convers. Manage.*, vol. 228, Jan. 2021, Art. no. 113692.

[22] D. Yousri, S. B. Thanikanti, D. Allam, V. K. Ramachandaramurthy, and M. B. Eteiba, "Fractional chaotic ensemble particle swarm optimizer for identifying the single, double, and three diode photovoltaic models' parameters," *Energy*, vol. 195, Mar. 2020, Art. no. 116979.

[23] T. S. Babu, D. Yousri, and K. Balasubramanian, "Photovoltaic array reconfiguration system for maximizing the harvested power using population-based algorithms," *IEEE Access*, vol. 8, pp. 109608–109624, 2020.

[24] D. Yousri, T. S. Babu, E. Beshr, M. B. Eteiba, and D. Allam, "A robust strategy based on marine predators algorithm for large scale photovoltaic array reconfiguration to mitigate the partial shading effect on the performance of PV system," *IEEE Access*, vol. 8, pp. 112407–112426, 2020.

[25] D. Yousri, T. S. Babu, and A. Fathy, "Recent methodology based Harris hawks optimizer for designing load frequency control incorporated in multi-interconnected renewable energy plants," *Sustain. Energy, Grids Netw.*, vol. 22, Jun. 2020, Art. no. 100352.

[26] T. S. Babu, N. Rajasekar, and K. Sangeetha, "Modified particle swarm optimization technique based maximum power point tracking for uniform and under partial shading condition," *Appl. Soft Comput.*, vol. 34, pp. 613–624, Sep. 2015.

[27] T. S. Babu, J. P. Ram, T. Dragicevic, M. Miyatake, F. Blaabjerg, and N. Rajasekar, "Particle swarm optimization based solar PV array reconfiguration of the maximum power extraction under partial shading conditions," *IEEE Trans. Sustain. Energy*, vol. 9, no. 1, pp. 74–85, Jan. 2018.

[28] K. Li and Y. Wang, "Maximum torque per ampere (MTPA) control for IPMSM drives based on a variable-equivalent-parameter MTPA control law," *IEEE Trans. Power Electron.*, vol. 34, no. 7, pp. 7092–7102, Jul. 2019.

CHIRANJIT SAIN received the B.Tech. degree in electrical engineering from the Maulana Abul Kalam Azad University of Technology, Kolkata, India, the M.Tech. degree from the Department of Electrical Engineering, National Institute of Technical Teachers Training and Research (NITTTR), Kolkata, in the specialization of mechatronics engineering, and the Ph.D. degree in electrical engineering from the National Institute of Technology Meghalaya, India, in 2019. He has been working an Assistant Professor with the Department of Electrical Engineering, Siliguri Institute of Technology, Siliguri, India, since 2010. He is an Associate Member of the Institution of Engineers (India). He has over ten years of academic experience, five years of research experience, and one year of industrial experience. His current research of interests include senorless and vector control of permanent magnet motor drives, digital control in power electronics converters, electric vehicles, design and optimization of electrical machines, and soft-computing analysis. He is currently serving as a reviewer for some reputed journals, like IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—II: EXPRESS BRIEF, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, *Electric Power Components and Systems* (Taylor & Francis), and Inderscience publications.

PABITRA KUMAR BISWAS (Member, IEEE) received the B.Tech. degree from the Asansol Engineering College, WBUT, Asansol, India, the M.E. degree from Bengal Engineering and Science University, India, and the Ph.D. degree in electrical engineering from the National Institute of Technology Durgapur, India. From July 2007 to February 2015, he served as an Assistant Professor in electrical engineering at the Asansol Engineering College. He is currently working as an Assistant Professor and the Head of the Department in Electrical Engineering at the National Institute of Technology Mizoram, India. He has published a numbers of research papers in national/international conference records/journals. His research interests include electromagnetic levitation systems, active magnetic bearing, and power electronics.

PRIYA RANJAN SATPATHY received the B.Tech. degree in electrical engineering and the M.Tech. degree in renewable energy engineering and management (electrical) from Siksha 'O' Anusandhan University, Bhubaneswar, India. He is currently working as a Research Scholar with the Department of Electrical Engineering, ITER, SOA Deemed to be University. Recently, he qualified the Senior Research Fellow (SRF) interview by the Council of Scientific and Industrial Research (CSIR), India. His area of interests include solar power systems, PV array efficiency improvement and fault reduction, maximum power point tracking, and PV system design and installation. He has depth knowledge on different software used for PV system installation, such as PVSyst, PVSOL, Sketchup, and HelioScope. He has been acting as a reviewer for various reputed journals, such as IEEE ACCESS, IEEE TRANSACTIONS, Elsevier, Wiley, and Taylor & Francis.

THANIKANTI SUDHAKAR BABU (Senior Member, IEEE) received the B.Tech. degree from Jawaharlal Nehru Technological University, Anantapur, India, in 2009, the M.Tech. degree in power electronics and industrial drives from Anna University, Chennai, India, in 2011, and the Ph.D. degree from VIT University, Vellore, India, in 2017.

He is currently working as an Associate Professor with the Department of Electrical Engineering, Chaitanya Bharathi Institute of Technology (CBIT), Hyderabad, India. He had completed his Postdoctoral Researcher Fellowship from the Institute of Power Engineering, Universiti Tenaga Nasional (UNITEN), Malaysia. Before to that, he was worked as an Assistant Professor at the School of Electrical Engineering, VIT University. He has published more than 60 research articles in various renowned international journals. His research interests include the design and implementation of solar PV systems, renewable energy resources, power management for hybrid energy systems, storage systems, fuel cell technologies, electric vehicles, and smart grids. He has been acting as an editorial board member and a reviewer for various reputed journals, such as IEEE ACCESS, IET, Elsevier, and Taylor & Francis.

HASSAN HAES ALHELOU (Senior Member, IEEE) is currently a Faculty Member of Tishreen University, Lattakia, Syria. He is also with University College Dublin, Dublin, Ireland. He has published more than 30 research papers in the high quality peer-reviewed journals and international conferences. He has also performed more than 160 reviews for high prestigious journals, including IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, *Energy Conversion and Management*, *Applied Energy*, and *International Journal of Electrical Power & Energy Systems*. He has participated in more than 15 industrial projects. His major research interests include power systems, power system dynamics, power system operation and control, dynamic state estimation, frequency control, smart grids, micro-grids, demand response, load shedding, and power system protection. He is included in the 2018 and 2019 Publons list of the top 1% best reviewer and researchers in the field of engineering. He was a recipient of the Outstanding Reviewer Award from *Energy Conversion and Management* journal, in 2016, *ISA Transactions* journal, in 2018, *Applied Energy* journal, in 2019, and many other awards. He was a recipient of the Best Young Researcher in the Arab Student Forum Creative among 61 researchers from 16 countries at Alexandria University, Egypt, in 2011.

• • •