Indonesian Journal of Electrical Engineering and Computer Science
Vol. 33, No. 2, February 2024, pp. 746~756
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v33.i2.pp746-756

A novel 7-level reduced-switch MLI topology fed PMSM drive for electric vehicle system

Chinta Anil Kumar[1], Kandasamy Jothinathan[1], Lingineni Shanmukha Rao[2]
[1]Department of Electrical and Electronics Engineering, Annamalai University, Chidambaram, India
[2]Department of Electrical and Electronics Engineering, Kallam Haranadhareddy Institute of Technology, Guntur, India

Article Info

Article history:

Received Sep 21, 2023
Revised Nov 16, 2023
Accepted Nov 17, 2023

Keywords:

Electric vehicles
Multilevel inverters
PMSM drive
Reduced-switch topology
Total harmonic distortion

ABSTRACT

The compact and efficient design motivates the renewable energy-powered permanent magnet synchronous motor drive for electric vehicle applications. The available renewable energy is interfaced with a power drive by employing an electronic commutator such as a conventional 3-level inverter. But, the multilevel inverter produces favorable merits by producing staircase output voltage from several input direct current (DC) sources. The cascaded H-bridge multilevel inverter plays a significant role in many applications, but it was developed only for limited voltage levels. The major problem in cascaded h-bridge multilevel inverter (CHBMLI) requires more switching devices for higher voltage levels, which increases the size, cost and space of the electric vehicle (EV). To overcome above-mentioned problems, a new objective has been developed by employing the novel Reduced-switch multilevel inverter topology for higher voltage levels. This improves the voltage quality and reducing the harmonic level, and common-mode voltage issues. The main contribution of this work is, developing the novel 5-level, 7-level reduced-switch multilevel inverter (RSMLI) topologies with reduced switching devices with favourable merits over CHBMLI topology. Finally, the performance of proposed novel 5-level and 7-level RSMLI topologies fed PMSM drive for EV system has been verified, by using MATLAB/Simulink computing tool, and simulation results are presented with comparisons.

Corresponding Author:

Chinta Anil Kumar
Department of Electrical and Electronics Engineering, Annamalai University
Chidamabaram, Tamilnadu, India
Email: chanilkumar.eee@gmail.com

1. INTRODUCTION

In today's socio-economic outlook, the growth of a society is heavily reliant on the type of electrical power generation. In this regard, power engineers are being compel to produce energy by using alternate or renewable energy sources (RES) operated electric vehicle (EV) drive system [1]–[6], it reduces the usage of fossil fuels, and greenhouse gases [7]. Amid various RES, the solar-photovoltaic (PV) array plays a significant role in standalone load-connected systems due to its virtuous, eco-friendly, easy erection, low maintenance, flexible power source, more operating life, no fuel cost, and harmless materials [8], [9]. In this context, permanent magnet synchronous motors (PMSM) have greater popularity over AC/DC motors, because of their light/simple structures, wide speed ranges, robustness, more overload capability, ease of control because of high torque-inertia ratio, low inertia rotor, low noise performance, and maximum efficiency [10]. Nowadays, the solar-PV system produces bulk power; it can generate 35% more power the petrol and/or diesel-operated vehicles. The solar-PV power varies during variations in irradiance and temperature levels, extracting the solar-PV power with ease controlling through a maximum-power point (MPP) tracker [11].

The obtained solar-PV power from solar roof-top is directly connected to EV batteries by employing a DC-DC boost converter which is directly integrated into the EV's inbuilt DC-bus for charging the batteries through bidirectional power flow. The available DC power at the DC bus is used to energize the stator windings of the PMSM drive through an electronic commutator such as a conventional 3-level voltage-source inverter (VSI) with a drive controller. The roof-top solar-PV-based EV charging system is depicted in Figure 1.

The conventional 3-level VSI module has many limitations such as high common-mode voltage, square-wave voltage, reverse-voltage limiting on switches, more harmonic levels, high dv/dt and di/dt stress, and low efficiency. These limitations in the 3-level VSI module are reduced and replaced with a multilevel inverter (MLI) topology for high-power/medium-voltage level applications [12]. Generally, MLI offers affirmative advantages such as low common-mode voltage, the superior quality of output RMS voltage, reduced harmonic level, low dv/dt and di/dt stress and maximum efficiency. The MLI produces staircase voltage at output terminals from several input DC voltages which is attained by operating the respective switches in a definite switching pattern [13].

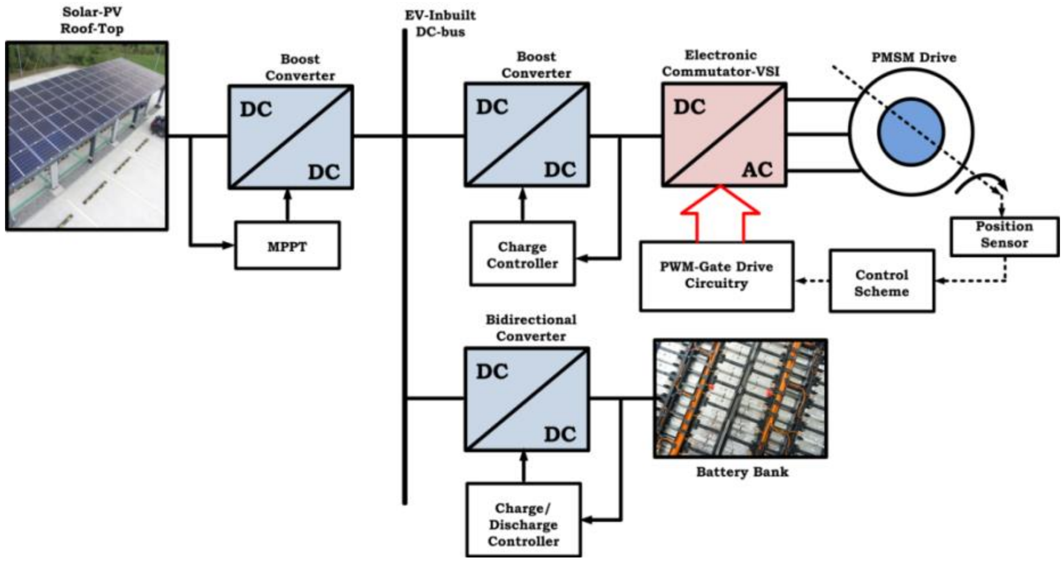

Figure 1. Roof-top solar-PV based EV charging system

MLIs have several topologies that are categorized based on their input DC sources, which can be either single or multiple input sources. Some prominent topologies are, diode-clamped multilevel inverter (DCMLI) [14] and flying-capacitor multilevel inverter (FCMLI) [15] topologies are well-suited for standalone drive applications. The cascaded h-bridge multilevel inverter (CHBMLI) topology [16] is dependent on multiple DC sources and is ideal for industrial drive applications. The CHB-MLI topology is a very well-known topology throughout all MLI's due to its compact nature, low-rated switching devices, simple circuitry, and ease of control. But, this CHB-MLI topology is designed only for limited voltage levels due to its increased number of switches for greater voltage levels which increases the cost, size, and design complexity of topology. The above-mentioned demerits are alleviated by introducing reduced-switch multilevel inverter (RSMLI) topologies; these are immensely preferable for higher voltage levels [17]. The RSMLI is the most significant topology which requires fewer switches, a very simple design, compact size, and reduced switch stress; maximizes efficiency levels for developing the same voltage levels at load terminals [18], [19].

In accordance with several literature studies exploring the major problems; a 5-level single-phase RSMLI topology is developed for medium-voltage applications in [20], by using 7 switches without any transformers. A solar-PV integrated single-stage 7-level MLI topology for a standalone system is proposed in [21], by using 12 switching devices without any clamping devices. A 7-level single-phase RSMLI topology is presented in [22], by employing 6 switches with an additional isolated transformer which increases the electromagnetic interference loss, size, and weight and is not suitable for higher levels. To establish the major objective, the novel RSMLI topology for the PMSM drive-fed EV system has been proposed with reduced switching devices and dis-integration of high-frequency isolated transformers [23], [24].

Most of the MLI topologies are controlled by pulse-width modulation (PWM) control methods, and some regular PWM methods are sinusoidal phase-shift PWM (SPSPWM) and level-shift PWM (SLSPWM) control methods [25]–[30]. But, it involves more carrier signals and complex drive circuitry for designing switching patterns to generate required output voltage levels [31]–[38]. In this work, a novel 5-level, 7-level RSMLI topology has been proposed by employing a reduced number of switching devices. The performance of proposed novel 5-level and 7-level RSMLI topologies fed PMSM drive for EV system has been verified, by using MATLAB/Simulink tool, and simulation results are presented with comparative analysis.

2. PROPOSED METHOD

Figure 2 shows the block diagram of proposed 7-level RSMLI topology. It comprises of several components such as input DC source, input DC capacitors, MOSFET switches, resistive load and so on. In general, the proposed topology requires (n-2) MOSFET switches named as $S_{a.1}$, $S_{a.2}$, $S_{a.3}$, $S_{a.4}$, $S_{a.5}$; (n+1)/2 self-balanced input DC capacitors named as $C_{dca.1}$, $C_{dca.2}$, $C_{dca.3}$, $C_{dca.4}$, with across voltage of $V_{dca.1}$, $V_{dca.2}$, $V_{dca.3}$, $V_{dca.4}$ are energized by input DC voltage of $4V_{dca}$, respectively. The magnitude of DC capacitors is maintained as constant with equal value regarded to common DC voltage of RSMLI topology. The voltage across input DC capacitors is used to attain 7-level staircase voltage at output terminals by regulating the respective switches in proposed 7-level RSMLI topology through appropriate switching states received from gate-drive circuitry. The synthesization of several input DC voltages are used to attain required output AC voltage $V_{o.AC}$, consisting of 7-levels such as $0V_{dca}$, $+V_{dca}$, $+2V_{dca}$, $+3V_{dca}$, $-V_{dca}$, $-2V_{dca}$, $-3V_{dca}$, respectively. The mathematical relations of proposed 7-Level RSMLI topology is expressed as,
number of MOSFET switches (N_s) is required:

$$N_s = (n - 2) \tag{1}$$

number of input DC capacitors (N_{DC}) is required:

$$N_{DC} = \frac{(n+1)}{2} \tag{2}$$

number of possible operating modes (N_m):

$$N_m = 2\left(\frac{n+1}{2}\right) - 1 \tag{3}$$

number of voltage levels at output ($V_{o.AC}$) node:

$$V_O = (n_{DC} \times 2) - 1 \tag{4}$$

the switching states of proposed 7-level RSMLI is depicted in Table 1. It shows, “1” represents the ON-switches and “0” represents the OFF-switches, accordingly.

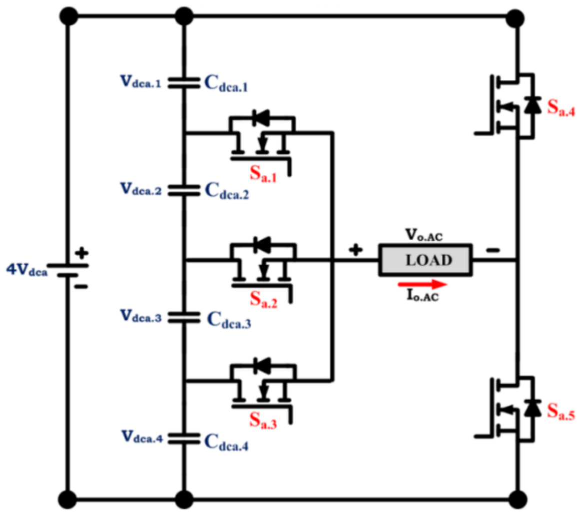

Figure 2. Proposed 7-level RSMLI topology

Table 1. Switching states of proposed 7-level RSMLI topology

Mode	Output voltage ($V_{O.AC}$)	Switching states				
		$S_{a.1}$	$S_{a.2}$	$S_{a.3}$	$S_{a.4}$	$S_{a.5}$
Level-1	0 V_{dca}	0	0	0	1	1
Level-2	+V_{dca}	0	0	1	0	1
Level-3	+2V_{dca}	0	1	0	0	1
Level-4	+3V_{dca}	1	0	0	0	1
Level-5	-V_{dca}	1	0	0	1	0
Level-6	-2V_{dca}	0	1	0	1	0
Level-7	-3V_{dca}	0	0	1	1	0

The switching pattern of the proposed 7-level RSMLI topology-fed PMSM drive is controlled through an appropriate reference voltage signal produced by the vector-oriented control (VOC) scheme. To establish the switching pattern, the classical SPSPWM and SLSPWM control methods are regularly employed. However, it involves more carrier signals and complex driver circuitry for designing switching patterns to generate required output voltage levels. In this regard, a new reduced-carrier based PWM control method has been developed in the proposed topology; it requires fewer carrier signals and, complex driver design over the SPSPWM and SLSPWM methods. For generation of 7-level voltage, the proposed RCPWM method requires 1 reference current Vref, which is produced by VOC and 3 triangular carriers. The triangular carriers are named Vca1, Vca2, and Vca3 with a carrier frequency of 3,050 Hz which are disposed vertically and slight changes in carrier magnitudes. The switching pattern and switching states of the new RCPWM method of the proposed 7-level RSMLI are depicted in Figures 3 and 4. The mathematical expressions of new RCPWM switching pattern is presented in (5).

$$S_{a.1} = (C.D) + (A.\bar{D}.\bar{B}.\bar{C})$$

$$S_{a.2} = (B.\bar{C}.D) + (B.\bar{C}.\bar{D})$$

$$S_{a.3} = (A.\bar{B}.D) + (C.\bar{D})$$

$$S_{a.4} = (\bar{A}.\bar{C}) + (A.B.C.\bar{D})$$

$$S_{a.5} = (A.B.C.D) + (A.\bar{D}) \quad (5)$$

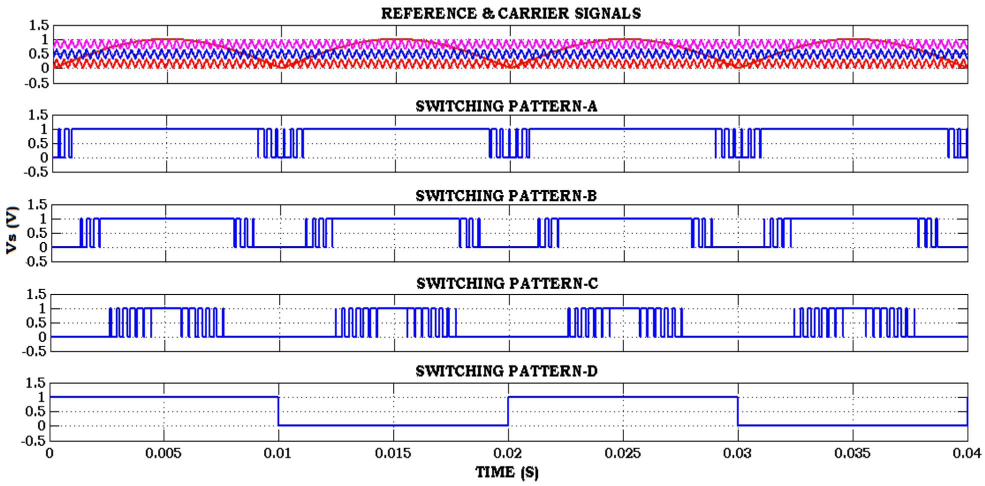

Figure 3. Switching pattern of RCPWM method

The overall schematic diagram of proposed 7-level RSMLI topology fed PMSM drive powered by roof-top solar-PV system is depicted in Figure 5. The performance of conventional 3-level, proposed novel 5-level and 7-level RSMLI topologies fed PMSM drive for EV system has been verified, by using MATLAB/SIMULINK tool, and simulation results are presented with comparative analysis. The system specifications are presented in Table 2.

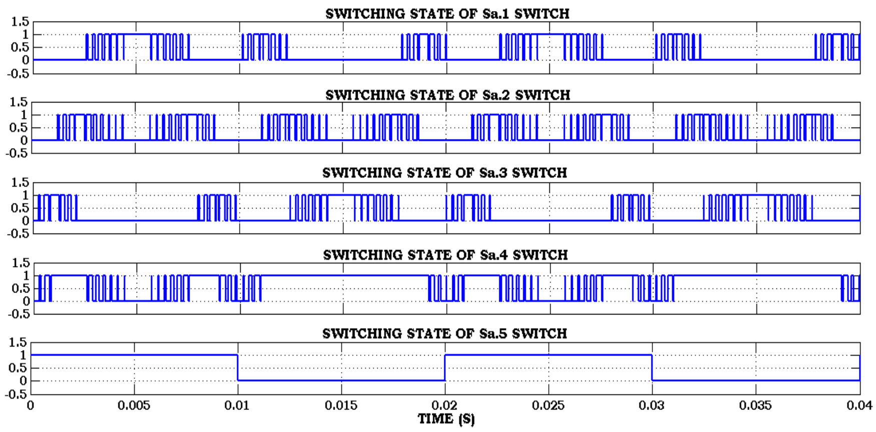

Figure 4. Switching states of RCPWM method

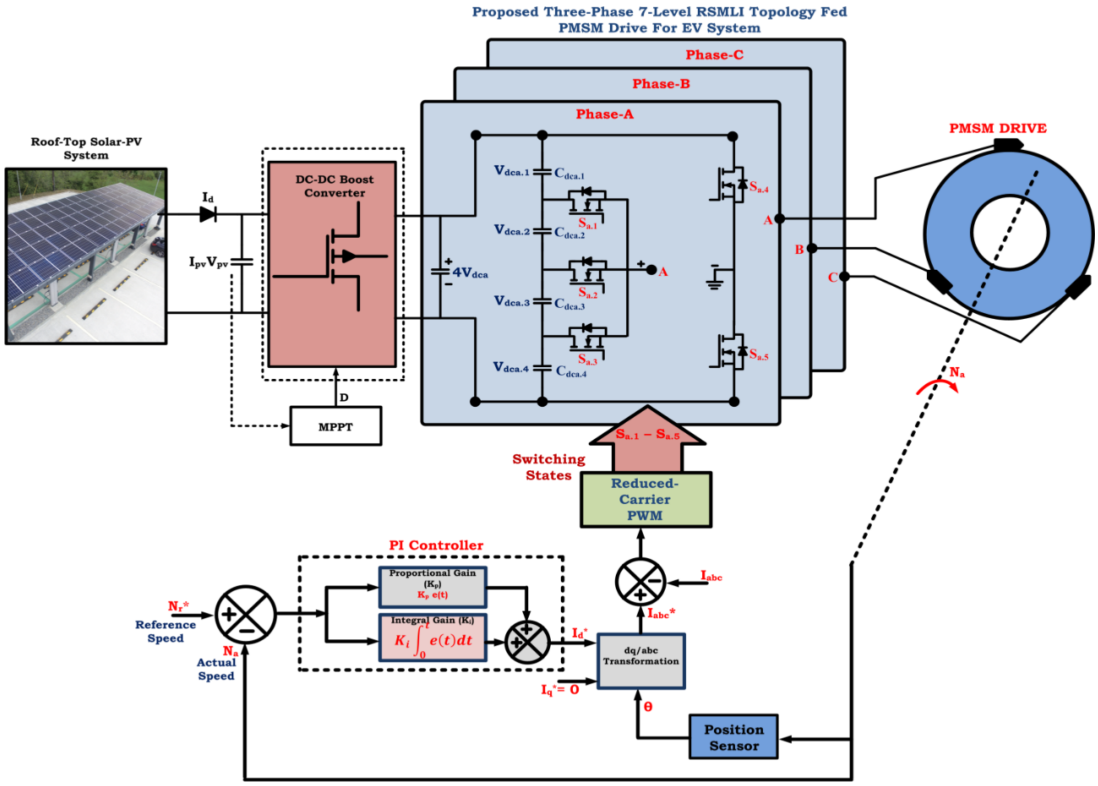

Figure 5. Overall schematic diagram of proposed 7-level RSMLI topology fed PMSM drive powered by roof-top solar-PV system

Table 2. System specifications

S. no	Specifications	Values
1	Input and output DC voltage	V_{in1}=100 V, V_o=520 V
2	Input DC capacitor	$V_{dca1234}$=130 V, $C_{dca1234}$=1000 µF
3	Switching frequency	Fs=3050 Hz
4	PMSM drive	P_o=5 KW, N_r=3,000 rpm, R_s=18.7Ω, L_s=0.0268µH, Voltage constant (Vpeak L-L/Krpm)=63.48

3. RESULTS AND DISCUSSION

3.1. Performance of conventional 3-level VSI fed PMSM drive for EV system

The simulation results of conventional 3-level VSI fed PMSM drive for EV system is illustrated in Figure 6. The 3-level VSI topology is powered with front-end DC-DC boost converter with input DC voltage of V_{in}-100 V, delivers the required DC voltage of V_{dca}-520 V with a load current of I_o-10 A is shown in Figure 6(a). In this case, the conventional 3-level VSI is act as the electronic commutator to drive the PMSM motor, which produces 3-level square-wave voltage of 520 V and attains sinusoidal three-phase stator current of 10 A is used to run the 5-kW rated PMSM motor drive is shown in Figures 6(b) and 6(c). The PMSM motor produced constant speed with a selected reference speed of N_r-3000 rpm is shown in Figure 6(d). During the starting mode, the PMSM drive generates the electromagnetic torque of nearly 8 Nm and 5 Nm in steady-state mode attains the selected load torque of 5 Nm to drive the EV system is shown in Figure 6(e). The rotor angle of PMSM motor is measured by sensing the hall signals produced by hall-sensors with a value of 6.28 rad/sec, which represents the sequential switching and continuous clock-wise 360º rotation of rotor is shown in Figure 6(f). The THD spectrum of 3-level output voltage is measured as 59.62% and the THD spectrum of stator current of PMSM is measured as 5.29%, which un-complying with IEEE standard values as shown in Figures 6(g) and 6(h).

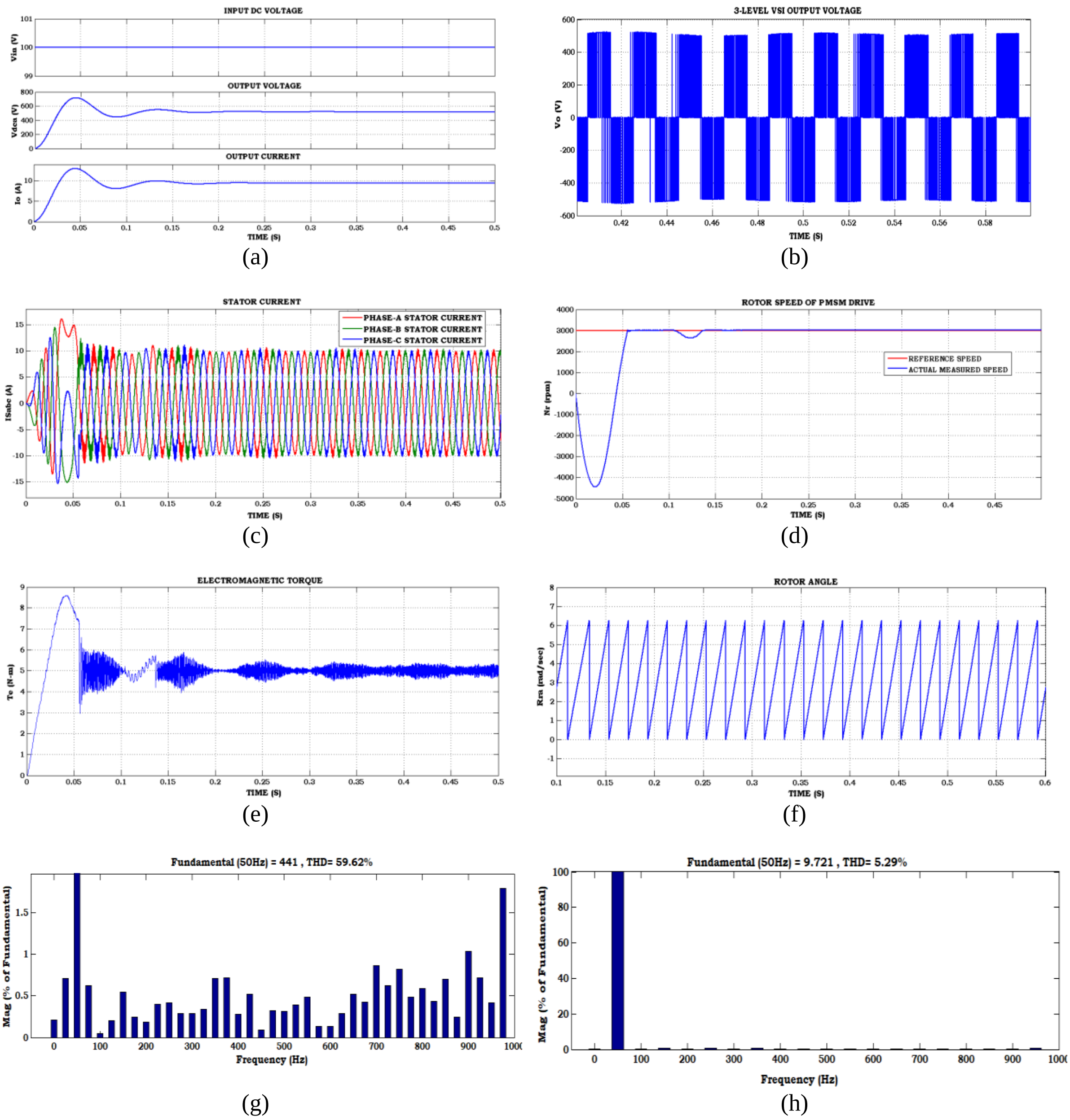

Figure 6. Simulation results of conventional 3-level VSI fed PMSM drive for EV system: (a) input DC voltage, output DC voltage, output current; (b) 3-level voltage of conventional VSI topology; (c) three-phase stator current of PMSM; (d) rotor speed of PMSM drive; (e) electromagnetic torque; (f) rotor angle of PMSM drive; (g) THD spectrum of 3-level output voltage; and (h) THD spectrum of stator current of PMSM

3.2. Performance of proposed 5-level RSMLI fed PMSM drive for EV system

The simulation results of proposed 5-level RSMLI topology fed PMSM drive for EV system is illustrated in Figure 7. The 5-level RSMLI topology is powered with front-end DC-DC boost converter with input DC voltage of V_{in}-100 V, delivers the required DC voltage of V_{dca}-520 V with a load current of I_o-10 A is shown in Figure 7(a). In this case, the proposed 5-level RSMLI is act as the electronic commutator to drive the PMSM motor, which produces 5-level stair-case voltage of 520 V and attains sinusoidal three-phase stator current of 10 A is used to run the 5-kW rated PMSM motor drive is shown in Figures 7(b) and 7(c). The PMSM motor produced constant speed with a selected reference speed of N_r-3000 rpm is shown in Figure 7(d). During the starting mode, the PMSM drive generates the electromagnetic torque of nearly 8 Nm and 5 Nm in steady-state mode attains the selected load torque of 5 Nm to drive the EV system is shown in Figure 7(e). The rotor angle of PMSM motor is measured by sensing the hall signals produced by hall-sensors with a value of 6.28 rad/sec, which represents the sequential switching and continuous clock-wise 360° rotation of rotor is shown in Figure 7(f). The THD spectrum of 5-level output voltage is measured as 25.35% and the THD spectrum of stator current of PMSM is measured as 2.53%, which is comply with IEEE-519/2014 standard values as shown in Figures 7(g) and 7(h).

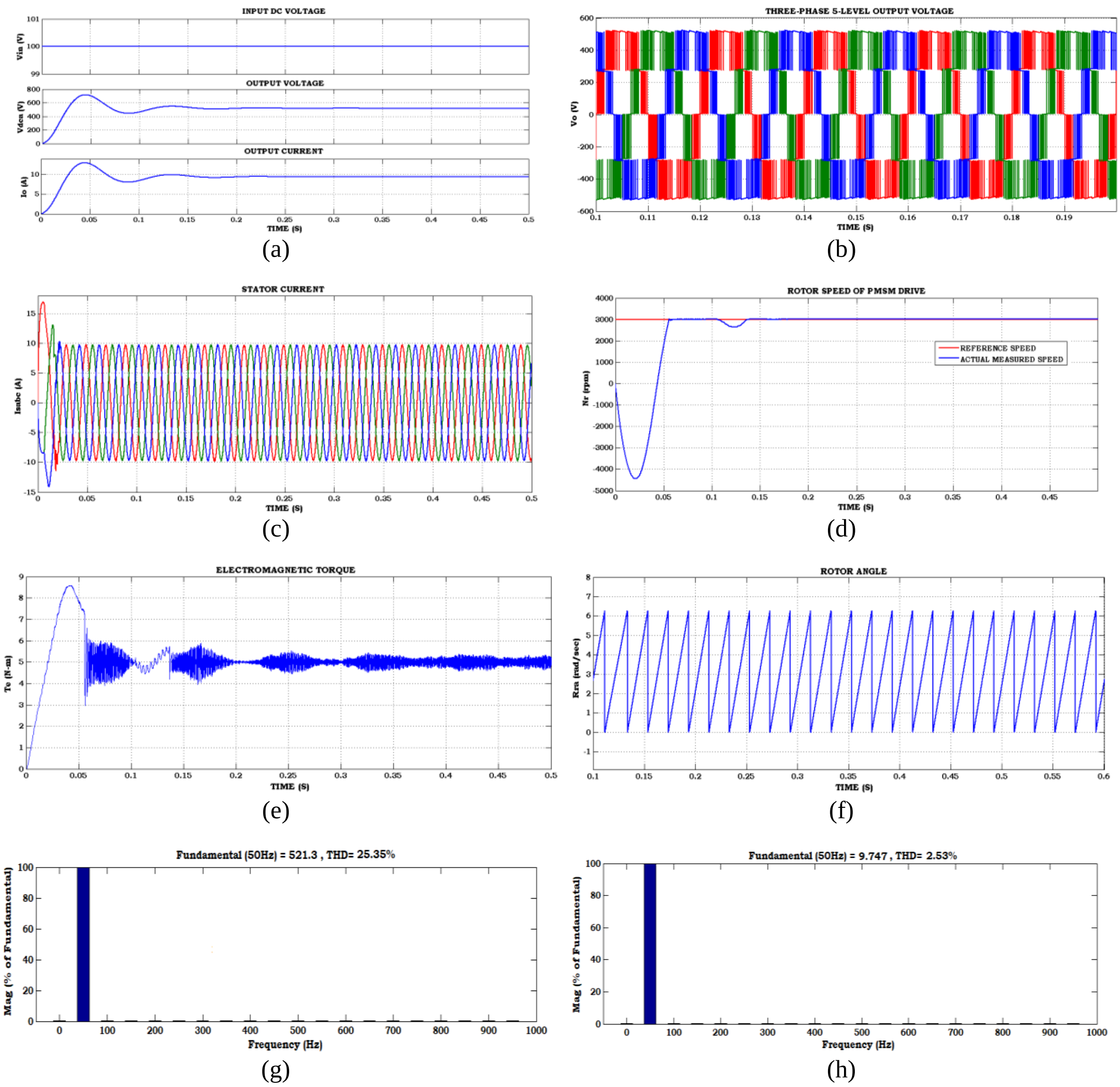

Figure 7. Simulation results of proposed 5-level RSMLI topology fed PMSM drive for EV system: (a) input DC voltage, output DC voltage, output current; (b) 5-level voltage of proposed RSMLI topology; (c) three-phase stator current of PMSM; (d) rotor speed of PMSM drive; (e) electromagnetic torque; (f) rotor angle of PMSM drive; (g) THD spectrum of 5-level output voltage; and (h) THD spectrum of stator current of PMSM

3.3. Performance of proposed 7-level RSMLI fed PMSM drive for EV system

The simulation results of proposed 7-level RSMLI topology fed PMSM drive for EV system is illustrated in Figure 8. The proposed 7-level RSMLI topology is powered with front-end DC-DC boost converter with input DC voltage of V_{in}-100 V, delivers the required DC voltage of V_{dca}-520 V with a load current of I_o-10 A is shown in Figure 8(a). In this case, the proposed 7-level RSMLI is act as the electronic commutator to drive the PMSM motor, which produces 5-level stair-case voltage of 520 V and attains sinusoidal three-phase stator current of 10 A is used to run the 5-kW rated PMSM motor drive is shown in Figures 8(b) and 8(c). The PMSM motor produced constant speed with a selected reference speed of N_r-3000 rpm is shown in Figure 8(d). During the starting mode, the PMSM drive generates the electromagnetic torque of nearly 8 Nm and 5 Nm in steady-state mode attains the selected load torque of 5 Nm to drive the EV system is shown in Figure 8(e). The rotor angle of PMSM motor is measured by sensing the hall signals produced by hall-sensors with a value of 6.28 rad/sec, which represents the sequential switching and continuous clock-wise 360º rotation of rotor is shown in Figure 8(f). The THD spectrum of 7-level output voltage is measured as 17.7% and the THD spectrum of stator current of PMSM is measured as 1.08%, which is comply with IEEE-519/2014 standard values as shown in Figures 8(g) and 8(h).

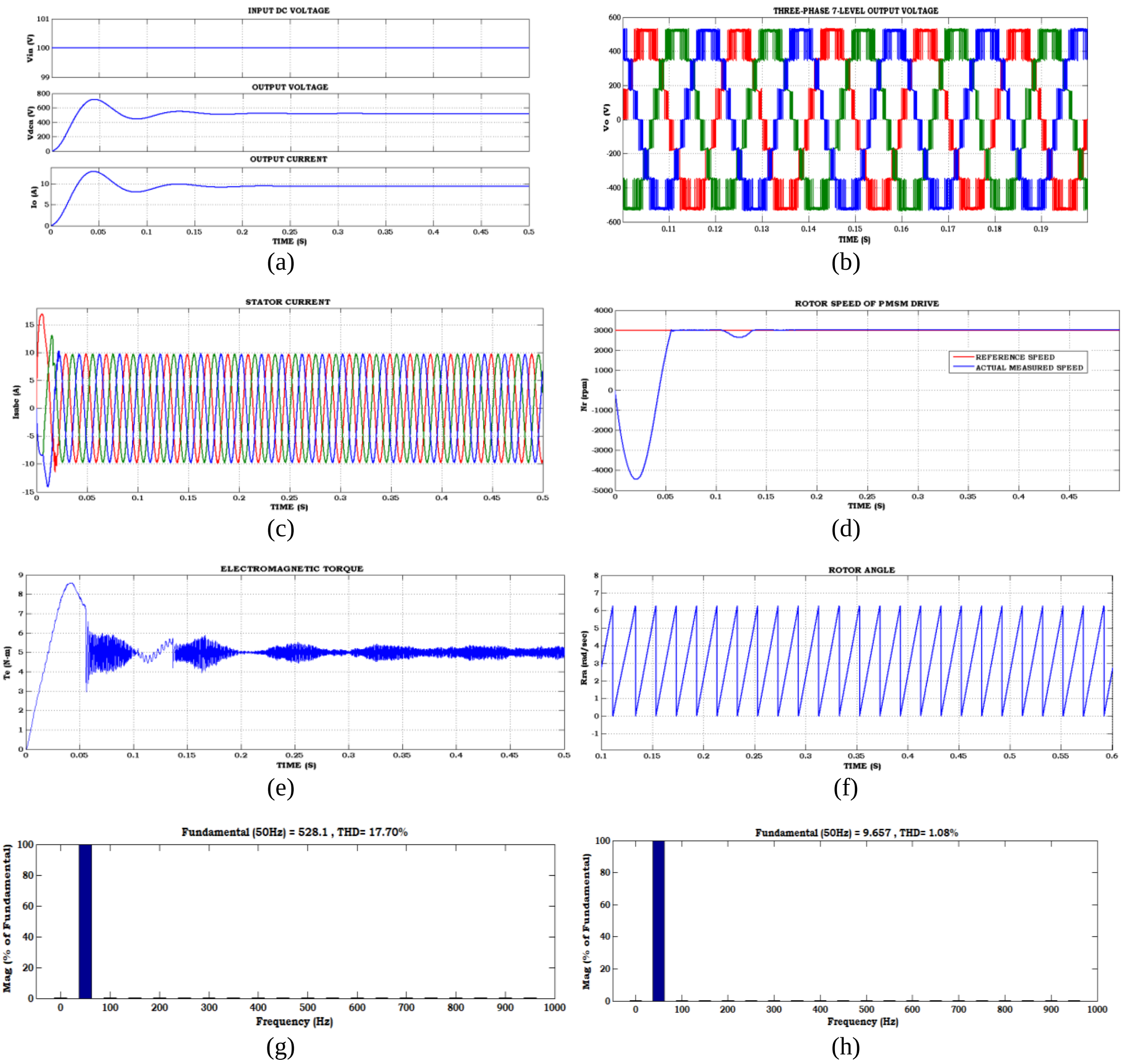

Figure 8. Simulation results of proposed 7-level RSMLI topology fed PMSM drive for EV system: (a) input DC voltage, output DC voltage; (b) output current, 7-level voltage of proposed RSMLI topology; (c) three-phase stator current of PMSM; (d) rotor speed of PMSM drive; (e) electromagnetic torque; (f) rotor angle of PMSM drive; (g) THD spectrum of 7-level output voltage; and (h) THD spectrum of stator current of PMSM

The THD comparison and graphical view of conventional 3-level VSI and proposed 5-level, 7-level RSMLI topologies fed PMSM drive is depicted in Table 3 and Figure 9. The proposed 5-level RSMLI topology produces the better reduction of THD response and attains good quality RMS voltage over the conventional 3-level VSI and proposed 5-level RSMLI topologies. Moreover, the stator current THD of proposed 7-level RSMLI topology driven by PMSM produces low harmonic content over the 3-level VSI and proposed 5-level RSMLI topologies. The comparison of switching devices required for 7-Level voltage under conventional and proposed RSMLI topologies is illustrated in Table 4.

Table 3. THD comparison

THD (%)	Output voltage	Stator current
Conventional 3-level VSI fed PMSM drive	59.62%	5.92%
Proposed 5-level RSMLI Fed PMSM drive	25.35%	2.53%
Proposed 5-level RSMLI Fed PMSM drive	17.7%	1.08%

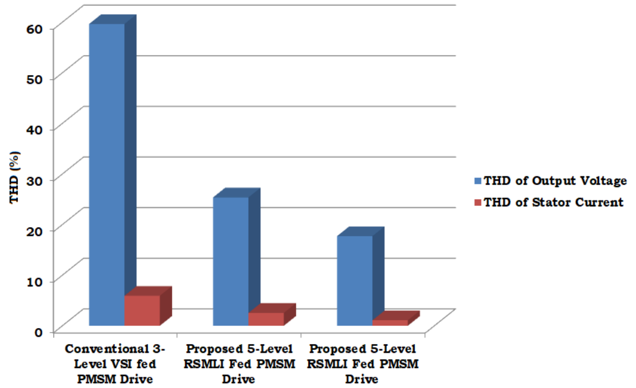

Figure 9. Graphical view of THD comparisons

Table 4. Comparison of switching devices required for 7-level voltage under conventional and proposed RSMLI topologies

Topologies switching devices	Conventional 7-level MLI topologies			Conventional 7-level RSMLI topology [22]	Proposed 7-level RSMLI topology
	DCMLI topology [14]	FCMLI topology [15]	CHBMLI topology [16]		
Main IGBT switches	12	12	12	7	5
Input DC sources	6	6	6	3	1
Clamping diodes	30	0	0	0	0
Balancing capacitors	0	15	0	0	0
Body diodes	12	12	12	7	5
High frequency transformers	0	0	0	2	0

4. CONCLUSION

The design, operation and performance of proposed 7-level RSMLI topology has been evaluated which is highly preferable for energizing the PMSM drive for EV system. Over the conventional 3-level VSI topology, the significant merits are compact size, fewer switches, low common-mode voltage, superior quality of output RMS voltage, reduced harmonic level, low dv/dt and di/dt stress and maximum efficiency, so on. Moreover, the new RCPWM control method using 3 carriers which have simple drive circuitry, low computational delay for furnishing appropriate switching pattern to 7-level RSMLI topology over the SPSPWM and SLSPWM methods. The proposed 7-level RSMLI topology requires very-low switching devices, no need of any high-frequency isolated transformers which reduces the complexity, size and cost of entire system. The performance of proposed 7-level RSMLI topology fed PMSM drive for EV system is verified, the outcome THD results are well-complying with IEEE-519/2014 standards.

REFERENCES

[1] I. Husain *et al.*, "Electric drive technology trends, challenges, and opportunities for future electric vehicles," *Proceedings of the IEEE*, vol. 109, no. 6, pp. 1039–1059, Jun. 2021, doi: 10.1109/JPROC.2020.3046112.

[2] B. Maclnnis and J. A. Krosnick., "Climate insights 2020: electric vehicles," *Resources for the Future (RFF)*. p. 32, 2020, [Online]. Available: https://www.rff.org/publications/reports/climateinsights2020-electric-vehicles.

[3] S. J. Rind, Y. Ren, Y. Hu, J. Wang, and L. Jiang, "Configurations and control of traction motors for electric vehicles: a review," *Chinese Journal of Electrical Engineering*, vol. 3, no. 3, pp. 1–17, Dec. 2017, doi: 10.23919/CJEE.2017.8250419.

[4] J. C. Gómez and M. M. Morcos, "Impact of EV battery chargers on the power quality of distribution systems," *IEEE Transactions on Power Delivery*, vol. 18, no. 3, pp. 975–981, Jul. 2003, doi: 10.1109/TPWRD.2003.813873.

[5] K. J. Dyke, N. Schofield, and M. Barnes, "The impact of transport electrification on electrical networks," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 3917–3926, Dec. 2010, doi: 10.1109/TIE.2010.2040563.

[6] O. N. Nezamuddin, C. L. Nicholas, and E. C. Dos Santos, "The problem of electric vehicle charging: state-of-the-art and an innovative solution," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 5, pp. 4663–4673, May 2022, doi: 10.1109/TITS.2020.3048728.

[7] B. Banfield, P. Ciufo, and D. A. Robinson, "The technical and economic benefits of utility sponsored renewable energy integration," in *2017 Australasian Universities Power Engineering Conference, AUPEC 2017*, Nov. 2018, vol. 2017-November, pp. 1–6, doi: 10.1109/AUPEC.2017.8282489.

[8] M. Shafiullah, S. D. Ahmed, and F. A. Al-Sulaiman, "Grid integration challenges and solution strategies for solar pv systems: a review," *IEEE Access*, vol. 10, pp. 52233–52257, 2022, doi: 10.1109/ACCESS.2022.3174555.

[9] R. Panigrahi, S. K. Mishra, and S. C. Srivastava, "Grid integration of small-scale photovoltaic systems-a review," in *2018 IEEE Industry Applications Society Annual Meeting, IAS 2018*, Sep. 2018, pp. 1–8, doi: 10.1109/IAS.2018.8544503.

[10] C. Sain, P. K. Biswas, P. R. Satpathy, T. S. Babu, and H. H. Alhelou, "Self-controlled PMSM drive employed in light electric vehicle-dynamic strategy and performance optimization," *IEEE Access*, vol. 9, pp. 57967–57975, 2021, doi: 10.1109/ACCESS.2021.3072910.

[11] E. Mattos, A. M. S. S. Andrade, G. V. Hollweg, J. R. Pinheiro, and M. L. Da Silva Martins, "A review of boost converter analysis and design in aerospace applications," *IEEE Latin America Transactions*, vol. 16, no. 2, pp. 305–313, Feb. 2018, doi: 10.1109/TLA.2018.8327380.

[12] H. Abu-Rub, J. Holtz, J. Rodriguez, and G. Baoming, "Medium-voltage multilevel converters State of the art, challenges, and requirements in Industrial applications," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 8, pp. 2581–2596, Aug. 2010, doi: 10.1109/TIE.2010.2043039.

[13] L. G. Franquelo, J. Rodriguez, J. I. Leon, S. Kouro, R. Portillo, and M. A. M. Prats, "The age of multilevel converters arrives," *IEEE Industrial Electronics Magazine*, vol. 2, no. 2, pp. 28–39, Jun. 2008, doi: 10.1109/MIE.2008.923519.

[14] J. Rodriguez, S. Bernet, P. K. Steimer, and I. E. Lizama, "A survey on neutral-point-clamped inverters," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2219–2230, Jul. 2010, doi: 10.1109/TIE.2009.2032430.

[15] T. Modeer, N. Pallo, T. Foulkes, C. B. Barth, and R. C. N. Pilawa-Podgurski, "Design of a GaN-based interleaved nine-level flying capacitor multilevel inverter for electric aircraft applications," *IEEE Transactions on Power Electronics*, vol. 35, no. 11, pp. 12153–12165, Nov. 2020, doi: 10.1109/TPEL.2020.2989329.

[16] K. N. V. Prasad, G. R. Kumar, T. V. Kiran, and G. S. Narayana, "Comparison of different topologies of cascaded H-bridge multilevel inverter," in *2013 International Conference on Computer Communication and Informatics, ICCCI 2013*, Jan. 2013, pp. 1–6, doi: 10.1109/ICCCI.2013.6466135.

[17] P. Omer, J. Kumar, and B. S. Surjan, "A Review on reduced switch count multilevel inverter topologies," *IEEE Access*, vol. 8, pp. 22281–22302, 2020, doi: 10.1109/ACCESS.2020.2969551.

[18] M. Sarebanzadeh, M. A. Hosseinzadeh, C. Garcia, E. Babaei, S. Islam, and J. Rodriguez, "Reduced switch multilevel inverter topologies for renewable energy sources," *IEEE Access*, vol. 9, pp. 120580–120595, 2021, doi: 10.1109/ACCESS.2021.3105832.

[19] P. R. Bana, K. P. Panda, R. T. Naayagi, P. Siano, and G. Panda, "Recently developed reduced switch multilevel inverter for renewable energy integration and drives application: topologies, comprehensive analysis and comparative evaluation," *IEEE Access*, vol. 7, pp. 54888–54909, 2019, doi: 10.1109/ACCESS.2019.2913447.

[20] V. J. Ramaiah and K. S. Kumar, "A single-phase 5-level inverter topology with reduced semiconductor switches," in *Proceedings of 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2018*, Dec. 2018, pp. 1–5, doi: 10.1109/PEDES.2018.8707786.

[21] A. Srivastava and S. P. Singh, "Performance analysis of single stage standalone PV fed novel three level inverter," in *1st IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems, ICPEICES 2016*, Jul. 2016, pp. 1–5, doi: 10.1109/ICPEICES.2016.7853365.

[22] V. S. K. Prasadarao, S. Peddapati, and S. V. K. Naresh, "A single phase seven-level MLI with reduced number of switches employing a PV Fed SIMO DC-DC converter," in *2020 IEEE Students' Conference on Engineering and Systems, SCES 2020*, Jul. 2020, pp. 1–6, doi: 10.1109/SCES50439.2020.9236755.

[23] M. V. Krishna, G. Satyanarayana, K. L. Ganesh, and D. Ravikiran, "THD optimization of sequential switching technique based hybrid IPD modulation scheme for CMLI," in *2014 International Conference on Science Engineering and Management Research, ICSEMR 2014*, Nov. 2014, pp. 1–7, doi: 10.1109/ICSEMR.2014.7043573.

[24] K. V. K. Varma, K. Sirisha, G. Satyanarayana, and K. L. Ganesh, "Optimal PWM strategy for 11-level series connected multilevel converter using hybrid PV/FC/BESS source," in *2014 International Conference on Circuits, Power and Computing Technologies, ICCPCT 2014*, Mar. 2014, pp. 686–691, doi: 10.1109/ICCPCT.2014.7055042.

[25] G. Satyanarayana and K. L. Ganesh, "Grid integration of hybrid generation scheme for optimal switching pattern based asymmetrical multilevel inverter," in *Lecture Notes in Electrical Engineering*, vol. 326, Springer India, 2015, pp. 295–303.

[26] K. L. Ganesh, N. S. Naik, K. Narendra, and G. S. Narayana, "A newly designed asymmetrical multi-cell cascaded multilevel inverter for distributed renewable energy resources," *International Journal of Recent Technology and Engineering*, vol. 7, no. ICETESM18, pp. 248–255, 2019.

[27] R. Shriwastava *et al.*, "Performance analysis of FOC space vector modulation DCMLI driven PMSM drive," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 5, pp. 2682–2692, Oct. 2023, doi: 10.11591/eei.v12i5.4554.

[28] V. T. Ha and P. T. Giang, "A study on PMSM drive systems fed by multi-level inverter using linear quadratic regulator control for electric vehicle applications," *Telkomnika (Telecommunication Computing Electronics and Control)*, vol. 21, no. 4, pp. 917–925, Aug. 2023, doi: 10.12928/TELKOMNIKA.v21i4.24432.

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

[30] K. Saleh and M. Sumner, "Multi-dimension SVPWM-based sensorless control of 7-phase PMSM drives," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 2, pp. 689–703, Apr. 2023, doi: 10.11591/eei.v12i2.4665.

[31] B. Adda, H. Kada, N. Aouadj, and K. A. Belhia, "New independent control of a Bi machine system powered by a multi-leg inverter applied to four in-wheel motor drive electric vehicle," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 1, pp. 614–621, Mar. 2023, doi: 10.11591/ijpeds.v14.i1.pp614-621.

[32] K. M. Naikawadi, S. M. Patil, K. Kalantri, and M. R. Dhanvijay, “Comparative analysis of features of online numerical methods used for parameter estimation of PMSM,” *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 4, pp. 2172–2180, Dec. 2022, doi: 10.11591/ijpeds.v13.i4.pp2172-2180.

[33] P. T. M. Sahridayan and R. Gopal, “Modeling and analysis of field-oriented control based permanent magnet synchronous motor drive system using fuzzy logic controller with speed response improvement,” *International Journal of Electrical and Computer Engineering*, vol. 12, no. 6, pp. 6010–6021, Dec. 2022, doi: 10.11591/ijece.v12i6.pp6010-6021.

[34] R. G. Shriwastava, M. P. Thakre, K. V. Bhadane, M. S. Harne, and N. B. Wagh, “Performance enhancement of DCMLI fed DTC-PMSM drive in electric vehicle,” *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 4, pp. 1867–1881, Aug. 2022, doi: 10.11591/eei.v11i4.3714.

[35] I. Djelamda and I. Bochareb, “Field-oriented control based on adaptive neuro-fuzzy inference system for PMSM dedicated to electric vehicle,” *Bulletin of Electrical Engineering and Informatics*, vol. 11, no. 4, pp. 1892–1901, Aug. 2022, doi: 10.11591/eei.v11i4.3818.

[36] H. Azoug, H. Belmili, and F. Bouazza, “Grid-connected control of pv-wind hybrid energy system,” *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 2, pp. 1228–1238, Jun. 2021, doi: 10.11591/ijpeds.v12.i2.pp1228-1238.

[37] I. Chinaeke-Ogbuka *et al.*, “A robust high-speed sliding mode control of permanent magnet synchronous motor based on simplified hysteresis current comparison,” *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 1, pp. 1–9, Mar. 2021, doi: 10.11591/ijpeds.v12.i1.pp1-9.

[38] M. Hasoun, A. El Afia, M. Khafallah, and K. Benkirane, “Field oriented control based on a 24-sector vector space decomposition for dual three-phase pmsm applied on electric ship propulsion,” *International Journal of Power Electronics and Drive Systems*, vol. 11, no. 3, pp. 1175–1187, Sep. 2020, doi: 10.11591/ijpeds.v11.i3.pp1175-1187.

BIOGRAPHIES OF AUTHORS

Chinta Anil Kumar currently research scholar in Department of Electrical and Electronics Engineering at Annamalai University, Annamalai Nagar, India. He has done B.Tech. in Electrical and Electronics Engineering from Acharya Nagarjuna University, Guntur, Andhra Pradesh, India and M.Tech. in Power Electronics and Drives from VIGNAN University, Guntur, Andhra Pradesh, India. His main research areas include renewable energy integration, and electrical vehicles. He can be contacted at email: chanilkumar.eee@gmail.com.

Dr. Kandasamy Jothinathan currently working as professor with the Department of Electrical and Electronics Engineering at Annamalai University, Annamalai Nagar, India. He received the B.E. degree Electrical and Electronics Engineering and the M.E. degree in power system from Annamalai University. He received Ph.D. degree in the year of 2017 from Annamalai University, Annamalai Nagar. His research topic includes power system operation and control, and security analysis. He can be contacted at email: jothi.eeau@yahoo.com.

Dr. Lingineni Shanmukha Rao received Ph.D. from Jawaharlal Nehru Technological University Hyderabad (JNTUH), Hyderabad, India in 2016 and M.Tech. in Electrical Power Engineering from Jawaharlal Nehru Technological University (J.N.T.U), Hyderabad, A.P, India in 2006. At Present he is working as Professor and Head of the Department Electrical and Electronics Engineering at Kallam Haranadhareddy Institute of Engineering and Technology, Guntur, A.P., India. He authored four books and published more than 27 research papers in international journals and conferences. His research interests include power system modeling and control, renewable energy sources, and soft computing techniques. He can be contacted at email: lsrlingineni@gmail.com.