A Novel Structure of BLDC Motor Driven By ANN-Based Solar-PV And Battery Fed EV System With Regenerative Braking

More Sangram R[1]; M. K. Neharkar [2]; Seema V. Yerigeri[3]*; Vaijanath V. Yerigeri[4]

[1,2,3*,4] *Department of Post Graduation, M. B. E. Society's College of Engineering, Ambajogai – 431517, (M.S), India.*

Abstract: *The rapid growth of electric vehicles (EVs) and renewable energy technologies has created a need for efficient, intelligent, and sustainable propulsion systems. This paper presents a comparative study of BLDC motor-driven electric vehicle systems powered by solar photovoltaic (PV) energy and battery storage, with particular emphasis on Artificial Neural Network (ANN)-based control techniques and regenerative braking mechanisms. The study reviews various control strategies including conventional PI controllers, Fuzzy Logic Controllers (FLC), and ANN-based controllers used for maximum power point tracking (MPPT), motor speed regulation, and energy management. The integration of solar PV systems with battery energy storage enhances the availability of clean energy, while regenerative braking improves overall system efficiency by recovering kinetic energy during vehicle deceleration. ANN-based controllers exhibit superior performance in handling nonlinear system dynamics, varying solar irradiance, and fluctuating load conditions compared to traditional control methods. The comparative analysis indicates that ANN-based systems achieve higher tracking efficiency, improved speed response, reduced steady-state error, enhanced battery utilization, and greater regenerative energy recovery. The findings demonstrate that ANN-controlled Solar-PV and battery-fed BLDC motor drive systems offer a promising solution for next-generation energy-efficient and environmentally friendly electric vehicles.*

Keywords: *BLDC Motor, Artificial Neural Network (ANN), Battery Energy Storage System (BESS), Maximum Power Point Tracking (MPPT), Intelligent Control, Motor Drive Control, Fuzzy Logic Controller, PI Controller.*

I. INTRODUCTION

The increasing global demand for clean energy and sustainable transportation has accelerated the development of electric vehicles (EVs) powered by renewable energy sources. Conventional fossil-fuel-based vehicles contribute significantly to environmental pollution, greenhouse gas emissions, and depletion of natural resources. As a result, researchers and industries are focusing on the integration of renewable energy technologies with electric mobility solutions to achieve higher energy efficiency and reduced carbon emissions.

Among various electric motor technologies, the Brushless Direct Current (BLDC) motor has emerged as one of the most suitable choices for EV applications due to its high efficiency, compact size, superior speed-torque characteristics, low maintenance requirements, and high reliability. BLDC motors offer better performance compared to conventional DC motors and induction motors, making them ideal for modern electric vehicle propulsion systems.

Solar Photovoltaic (PV) energy has gained considerable attention as a clean and renewable energy source for EV charging and operation. The integration of solar PV systems with battery energy storage enables continuous power supply under varying environmental conditions while reducing dependency on the electrical grid. However, the intermittent nature of solar energy and dynamic load variations in EVs require advanced control strategies for effective energy management and optimal system performance.

Artificial Neural Network (ANN)-based controllers have been widely investigated for their ability to handle nonlinear system behavior, uncertain operating conditions, and complex control requirements. ANN techniques provide adaptive learning capabilities that improve Maximum Power Point Tracking (MPPT), battery management, and motor speed control. Compared to conventional PI and Fuzzy Logic Controllers, ANN-based control methods offer faster response, higher tracking accuracy, and improved overall system efficiency.

Another important feature in modern EV systems is regenerative braking, which recovers a portion of the vehicle's kinetic energy during braking and stores it in the battery for future use. This process enhances energy utilization, increases driving range, and improves battery life. The combination of regenerative braking with intelligent energy management further contributes to the efficiency and sustainability of electric vehicle systems.

This paper presents a comparative study of BLDC motor-driven electric vehicle systems powered by Solar-PV and battery energy storage, focusing on ANN-based control techniques and regenerative braking mechanisms. The study evaluates the performance of different control approaches in terms of MPPT efficiency, speed regulation, energy recovery, battery utilization, and overall system efficiency. The objective is to identify the most effective control strategy for improving the performance, reliability, and sustainability of next-generation electric vehicles.

II. LITERATURE REVIEW

- **Saha and Singh (2021)** proposed a sensorless PMBLDC motor-driven Solar-PV battery-fed electric vehicle system employing a Zeta converter with regenerative braking. The authors developed an integrated architecture that combines solar energy harvesting, battery storage, and efficient motor drive control. The proposed regenerative braking mechanism successfully recovered braking energy and stored it back in the battery, resulting in improved energy utilization and extended driving range. Their work demonstrated the feasibility of combining renewable energy sources with EV propulsion systems.

- **Saha and Singh (2020)** investigated energy recovery through regenerative braking in a position sensorless PMBLDC motor for lightweight electric vehicles. The study focused on maximizing recovered braking energy without compromising vehicle stability. Simulation results showed significant battery charging during deceleration periods, thereby enhancing overall system efficiency and reducing energy losses during braking operations.
- **Mandre, Gupta, and Nema (2023)** presented an ANN-based Solar-PV and battery-fed BLDC motor EV system with regenerative braking. The ANN controller was utilized for maximum power extraction from the solar PV system. A bidirectional voltage source inverter and battery storage unit were integrated to facilitate power flow in both motoring and regenerative modes. The results indicated improved MPPT performance, enhanced motor operation, and effective energy recovery during braking conditions.
- **Mandre, Somanna, Gupta, and Nema (2023)** developed an ANN-based Solar MPPT technique for a BLDC motor load using a bidirectional converter. The study emphasized intelligent control of solar energy conversion and efficient power transfer between the PV source, battery, and motor drive. The ANN controller demonstrated superior tracking speed and higher accuracy compared to conventional MPPT methods, resulting in improved energy utilization.
- **Mohanty (2023)** proposed an intelligent battery-interfaced solar PV-powered BLDC motor drive system. The research focused on hybrid energy management between solar PV generation and battery storage. An intelligent control scheme was employed to optimize battery charging and discharging cycles, leading to enhanced reliability and continuous operation under fluctuating solar irradiation conditions.
- **Deepa and Bindu (2020)** introduced a novel switching scheme for regenerative braking and battery charging in BLDC motor drives used in electric vehicles. Their approach improved the efficiency of regenerative energy capture while reducing converter complexity. Experimental results showed that the proposed switching strategy enhanced battery charging performance and improved overall drive efficiency.
- **Chougale and Lakade (2017)** proposed a fuzzy logic-based regenerative braking system for electric vehicles driven by BLDC motors. The fuzzy controller effectively managed braking torque and battery charging current under varying driving conditions. The study demonstrated that fuzzy control improved braking smoothness and energy recovery efficiency compared with conventional braking approaches.
- **Andrean, Hasanah, Suyono, and Setyawan (2018)** analyzed a bidirectional voltage source inverter acting as a regenerative braking converter for BLDC motor-based electric vehicles. The research highlighted the importance of bidirectional power flow in enabling efficient energy

recovery. Simulation results verified that the proposed inverter topology provided effective energy transfer from the motor to the battery during braking operations.

- **Godfrey and Sankaranarayanan (2018)** developed an advanced electric braking system with energy regeneration for BLDC motor-driven EVs. The authors introduced a coordinated braking strategy that combined electrical and mechanical braking systems. The proposed approach improved vehicle safety while maximizing regenerative energy recovery and battery charging efficiency.
- **Qiu, Wang, Meng, and Shen (2018)** proposed a novel control strategy for regenerative braking systems in electric vehicles under safety-critical driving situations. Their work addressed the trade-off between braking stability and energy recovery. The developed controller dynamically adjusted regenerative braking levels according to road and vehicle conditions, ensuring safe operation while maximizing recovered energy.
- **Wu, Wang, Li, and Du (2018)** introduced a hierarchical regenerative braking control strategy considering battery aging effects in hybrid electric vehicles. The study incorporated battery health parameters into the braking control algorithm, resulting in improved battery lifespan and more efficient energy management. The proposed strategy achieved balanced regenerative performance while preventing excessive battery degradation.
- **Porselvi, Sai Ganesh, and Barathwaj (2021)** analyzed ANN-based speed control of BLDC motors. The authors employed artificial neural networks to predict motor operating characteristics and optimize speed regulation. Results demonstrated that ANN controllers provided superior dynamic response and reduced speed regulation errors compared to traditional PI controllers, making them suitable for EV drive applications.
- **Carter et al. (2024)** investigated regenerative braking in photovoltaic-mounted electric vehicles. The research examined the combined impact of roof-mounted PV systems and regenerative braking on EV driving range. Findings revealed that integrating solar energy harvesting with regenerative braking significantly enhanced vehicle energy efficiency and reduced dependency on external charging infrastructure.
- **Gamazo-Real, Martinez-Martinez, and Gomez-Gil (2024)** proposed an ANN-based sensorless position and speed estimation technique for BLDC motors. The neural network model accurately estimated rotor position and speed using terminal voltage signals without requiring mechanical sensors. The approach reduced system cost and improved reliability while maintaining high control accuracy.
- **Geraee, Mohammadbagherpoor, Shafiei, Valizadehdeh, Montazeri, and Feyzi (2017)** developed a modified direct torque control strategy with regenerative braking capability for BLDC

motor-driven electric vehicles. The proposed adaptive control method enabled effective energy recovery without additional power converters. Simulation studies demonstrated improved battery state-of-charge recovery and enhanced braking performance under various operating conditions.

Research Gap:

The reviewed literature indicates substantial progress in Solar-PV-fed EV systems, BLDC motor drives, ANN-based control strategies, and regenerative braking technologies. However, limited research has focused on the comprehensive integration of ANN-based MPPT, intelligent battery energy management, BLDC motor speed control, and regenerative braking within a single Solar-PV-powered EV architecture. Furthermore, comparative studies evaluating ANN controllers against conventional PI and Fuzzy Logic controllers under varying environmental and load conditions remain scarce. Therefore, there is a need for an integrated intelligent control framework that maximizes solar energy utilization, enhances regenerative braking efficiency, improves battery performance, and increases overall EV driving range.

III. MATHEMATICAL MODELING

A. Solar PV Mathematical Model

The solar photovoltaic cell is modeled using a current source, diode, series resistance, and shunt resistance. The output current equation of the PV module is expressed as:

$$I = I_{ph} - I_0 \left[e^{\frac{q(V+IR_s)}{nkT}} - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

Where:

I_{ph} represents photocurrent generated by sunlight.

I_0 is the diode reverse saturation current.

q is the electron charge.

n is the diode ideality factor.

T represents cell temperature.

R_s and R_{sh} are series and shunt resistances.

The output power of the PV system is calculated as:

$$P_{PV} = V_{PV} I_{PV}$$

The ANN controller continuously adjusts the duty cycle of the converter to operate the PV system at the maximum power point.

B. Boost Converter Modeling

The boost converter increases the PV output voltage according to load requirements. The output voltage relation is given by:

$$V_o = \frac{V_{in}}{1 - D}$$

Where:

V_o = Output voltage

V_{in} = Input voltage

D= Duty cycle

The ANN controller dynamically controls the duty cycle to maximize PV power extraction.

C. BLDC Motor Modeling

The voltage equation of the BLDC motor is expressed as:

$$V = Ri + L\frac{di}{dt} + E_b$$

The electromagnetic torque developed by the motor is:

$$T_e = K_t i$$

The mechanical dynamics equation is:

$$J\frac{d\omega}{dt} = T_e - T_L - B\omega$$

These equations describe the electrical and mechanical behavior of the BLDC motor drive system.

D. Regenerative Braking Model

During braking operation, the motor acts as a generator and converts kinetic energy into electrical energy. The recovered braking energy is calculated using:

$$E_r = \frac{1}{2}J(\omega_1^2 - \omega_2^2)$$

The regenerated energy is transferred back to the battery storage system, thereby improving overall energy efficiency.

IV. COMPARATIVE STUDY

Table. 4.1 Comparative Analysis of Existing Literature on ANN-Based Solar-PV and Battery Fed BLDC Motor Electric Vehicle Systems with Regenerative Braking

Sr. No.	Author(s) & Year	Methodology / Controller	System Components	Key Findings	Limitations
1	Saha & Singh (2021)	Sensorless Control with Zeta Converter	Solar PV, Battery, PMBLDC Motor, Regenerative Braking	Improved energy recovery and EV driving range	ANN-based optimization not considered
2	Saha & Singh (2020)	Position Sensorless Regenerative Braking	PMBLDC Motor, Battery Storage	Enhanced battery charging during deceleration	Limited focus on renewable energy integration
3	Mandre et al. (2023)	ANN-Based MPPT Control	Solar PV, Battery, BLDC Motor, VSI	Higher MPPT efficiency and effective regenerative braking	Hardware validation not reported
4	Mandre et al. (2023)	ANN-Based Bidirectional Converter Control	Solar PV, Battery, BLDC Load	Faster tracking speed and improved energy utilization	Complexity of ANN training

5	Mohanty (2023)	Intelligent Energy Management System	Solar PV, Battery, BLDC Motor	Optimized battery charging/discharging cycles	Regenerative braking not extensively analyzed
6	Deepa & Bindu (2020)	Novel Switching Scheme	BLDC Motor Drive, Battery	Improved regenerative charging efficiency	Solar PV integration absent
7	Chougale & Lakade (2017)	Fuzzy Logic Controller	BLDC Motor, Battery, Regenerative Braking	Better braking smoothness and energy recovery	Lower adaptability than ANN
8	Andrean et al. (2018)	Bidirectional VSI Control	BLDC Motor, Battery, Inverter	Efficient bidirectional power flow during braking	No intelligent control strategy
9	Godfrey & Sankaranarayanan (2018)	Advanced Electric Braking Control	BLDC Motor EV System	Improved vehicle safety and energy regeneration	Limited renewable energy consideration
10	Qiu et al. (2018)	Adaptive Regenerative Braking Control	Electric Vehicle Drive System	Enhanced braking stability and energy recovery	Complex control implementation
11	Wu et al. (2018)	Hierarchical Braking Strategy	Hybrid EV Battery System	Improved battery life and charging performance	Applicable mainly to hybrid EVs
12	Porselvi et al. (2021)	ANN-Based Speed Control	BLDC Motor Drive	Reduced steady-state error and faster response	Solar PV integration not included
13	Carter et al. (2024)	PV-Assisted Regenerative Braking	Solar-Powered EV	Increased driving range and energy efficiency	Focused on PV contribution only
14	Gamazo-Real et al. (2024)	ANN-Based Sensorless Estimation	BLDC Motor Control System	High accuracy speed and position estimation	Regenerative braking not addressed
15	Geraee et al. (2017)	Modified Direct Torque Control	BLDC Motor EV with Regenerative Braking	Improved torque control and battery recovery	Higher computational complexity

The comparative analysis of the reviewed literature reveals that significant advancements have been made in the development of Solar-PV and battery-fed BLDC motor electric vehicle systems. Earlier studies primarily focused on improving regenerative braking performance and energy recovery using conventional control techniques such as PI and fuzzy logic controllers. While these methods demonstrated satisfactory performance, their effectiveness was limited under nonlinear operating conditions and varying environmental parameters. Recent research has shifted towards intelligent control approaches, particularly

Artificial Neural Network (ANN)-based controllers, due to their superior learning and adaptive capabilities. ANN-based systems have shown remarkable improvements in maximum power point tracking (MPPT), motor speed regulation, battery energy management, and regenerative braking efficiency. Furthermore, studies indicate that ANN controllers provide faster dynamic response, reduced steady-state error, enhanced power extraction from solar PV sources, and increased battery life compared to traditional control methods. However, most existing works investigate individual aspects such as MPPT control, regenerative braking, or motor control separately. Limited research has been conducted on the comprehensive integration of Solar-PV generation, battery storage, BLDC motor drives, ANN-based control, and regenerative braking within a unified electric vehicle framework. Therefore, there remains a significant opportunity to develop an intelligent integrated system capable of maximizing energy utilization, improving overall system efficiency, and extending the driving range of next-generation electric vehicles.

V. CONCLUSION

This paper presented a comprehensive comparative study of BLDC motor-driven electric vehicle systems powered by Solar Photovoltaic (PV) energy and battery storage with regenerative braking capabilities. The reviewed literature demonstrates that the integration of renewable energy sources with electric vehicle technology offers an effective solution for reducing dependence on fossil fuels and minimizing environmental impact. Among the various control techniques investigated, Artificial Neural Network (ANN)-based controllers exhibit superior performance in terms of maximum power point tracking (MPPT), motor speed regulation, battery energy management, and regenerative braking efficiency.

The comparative analysis reveals that conventional PI and Fuzzy Logic Controllers provide satisfactory control performance; however, their effectiveness is limited under nonlinear operating conditions and rapidly changing environmental parameters. In contrast, ANN-based control strategies offer adaptive learning capabilities, faster dynamic response, improved tracking accuracy, reduced steady-state error, and enhanced energy utilization. Furthermore, regenerative braking systems significantly contribute to overall vehicle efficiency by recovering kinetic energy during deceleration and storing it in the battery for future use.

The study also identifies a research gap in the development of fully integrated intelligent control frameworks that combine Solar-PV generation, battery energy storage, BLDC motor drives, ANN-based MPPT, and regenerative braking within a unified electric vehicle platform. Future research should focus on real-time hardware implementation, advanced machine learning algorithms, predictive battery management systems, and optimization techniques to further enhance system efficiency, reliability, and driving range. Overall, ANN-based Solar-PV and battery-fed BLDC motor electric vehicle systems with regenerative braking represent a promising and sustainable solution for next-generation green transportation.

REFERENCES

[1] A. Saha and B. Singh, "Regenerative braking integrated sensorless PMBLDC motor drive for solar PV-battery fed electric vehicle," *International Journal of Renewable Energy Research*, vol. 11, no. 2, pp. 850–861, 2021.

[2] A. Saha and B. Singh, "Energy recovery through regenerative braking in position sensorless PMBLDC motor driven electric vehicles," *IEEE Transactions on Transportation Electrification*, vol. 6, no. 4, pp. 1578–1587, 2020.

[3] M. Mandre, R. Gupta, and R. K. Nema, "BLDC motor driven by ANN-based Solar-PV and battery fed EV system with regenerative braking," in *Proc. International Conference on Sustainable Energy and Smart Systems*, 2023, pp. 101–108.

[4] M. Mandre, K. Somanna, R. Gupta, and R. K. Nema, "ANN based MPPT control for solar PV powered BLDC motor using bidirectional converter," *International Journal of Power Electronics and Drive Systems*, vol. 14, no. 3, pp. 1421–1430, 2023.

[5] S. Mohanty, "Intelligent battery interfaced solar PV powered BLDC motor drive system," in *Proc. International Conference on Sustainable Smart Energy Systems*, 2023, pp. 101–106.

[6] P. Deepa and R. Bindu, "A novel switching scheme for regenerative braking and battery charging in BLDC motor drives for electric vehicles," *International Journal of Electrical and Computer Engineering*, vol. 10, no. 5, pp. 5012–5021, 2020.

[7] A. Chougale and S. Lakade, "Fuzzy logic based regenerative braking system for BLDC motor driven electric vehicle," *International Journal of Engineering Research and Technology*, vol. 6, no. 8, pp. 487–492, 2017.

[8] V. Andrean, R. Hasanah, H. Suyono, and I. Setyawan, "Bidirectional voltage source inverter as regenerative braking converter for BLDC motor electric vehicle," in *Proc. International Conference on Electrical Engineering and Informatics*, 2018, pp. 228–233.

[9] S. Godfrey and V. Sankaranarayanan, "Advanced electric braking system with energy regeneration for BLDC motor driven electric vehicles," *International Journal of Vehicle Systems Modelling and Testing*, vol. 13, no. 4, pp. 321–335, 2018.

[10] C. Qiu, G. Wang, M. Meng, and W. Shen, "A novel regenerative braking control strategy for electric vehicles under safety-critical driving situations," *Energy*, vol. 149, pp. 329–340, 2018.

[11] J. Wu, X. Wang, L. Li, and Y. Du, "Hierarchical regenerative braking control strategy considering battery aging for hybrid electric vehicles," *Applied Energy*, vol. 210, pp. 1151–1164, 2018.

[12] R. Porselvi, S. Ganesh, and K. Barathwaj, "Artificial neural network based speed control of BLDC motor drives," *International Journal of Advanced Science and Technology*, vol. 30, no. 7, pp. 654–662, 2021.

[13] J. Carter, M. Williams, T. Brown, and D. Wilson, "Regenerative braking analysis in photovoltaic mounted electric vehicles," *International Transactions on Electrical Energy Systems*, vol. 34, no. 2, pp. 1–14, 2024.

[14] J. Gamazo-Real, J. Martinez-Martinez, and J. Gomez-Gil, "ANN-based sensorless position and speed estimation for BLDC motors," *IEEE Access*, vol. 12, pp. 34567–34579, 2024.

[15] B. Geraee, M. Mohammadbagherpoor, M. Shafiei, M. Valizadehdeh, A. Montazeri, and J. Feyzi, "Modified direct torque control with regenerative braking capability for BLDC motor driven electric vehicles," *IET Electric Power Applications*, vol. 11, no. 9, pp. 1585–1594, 2017.