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Sensorless PMBLDC Motor Driven Solar-PV Battery Fed EV System with Regenerative Braking Employing Zeta Converter : A Review

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Abstract: *This review surveys recent research on sensorless permanent-magnet brushless DC (PMBLDC / PMBLDCM) motor drives for electric vehicles (EVs) powered by solar-PV + battery sources, with specific attention to regenerative-braking integration and Zeta (and related) DC–DC converters used for energy transfer and battery management. We summarize sensorless rotor-position/speed estimation methods (back-EMF, observers, sliding-mode, Luenberger, hybrid approaches), power-electronics topologies that enable bidirectional energy flow during braking (Zeta, SEPIC, single-stage Zeta-SEPIC hybrids, high-gain/bidirectional converters), and system-level designs that combine MPPT, battery charging, and regenerative capture. For each selected paper we give a focused paragraph describing methods, results, and relevance to sensorless PMBLDC + solar-PV EV architectures. We identify open problems — low-speed position estimation during startup, bidirectional converter efficiency, seamless MPPT + regenerative energy routing, and real-world validation — and propose research directions: robust low-speed observers, integrated single-stage bidirectional converters optimized for PV + regenerative flows, and hardware demonstrations on prototype EV platforms.*

Keywords*:* Sensorless control, PMBLDC, BLDC, back-EMF estimation, Zeta converter, bidirectional DC–DC, regenerative braking, solar-PV, battery-fed EV, MPPT, observer

I. INTRODUCTION

Electrified propulsion for light and micro EVs has motivated compact, efficient motor drives that minimize sensor cost and complexity while maximizing overall vehicle energy efficiency. Permanent-magnet BLDC motors are attractive for small EVs due to high torque density and simple inverter control; however, mechanical position sensors add cost, wiring complexity, and reliability concerns. Sensorless techniques (back-EMF sensing, observers, sliding-mode estimation, and hybrid approaches) eliminate position sensors but face challenges at low speed and during startup. Meanwhile, integrating on-vehicle solar PV and capturing regenerative braking energy demands power-electronics that can handle bidirectional energy flow between motor/generator, battery, and PV array — Zeta and related converters have been proposed as practical solutions because of their non-inverting buck/boost capability and flexible operating range. This review synthesizes the literature at the intersection of these topics: sensorless PMBLDC control, Zeta (and related) DC–DC converter architectures for PV + battery EVs, and system strategies for combining MPPT, battery charging, and regenerative energy capture.

The rapid depletion of fossil fuels and the growing environmental concerns have accelerated the global shift toward clean and sustainable transportation systems. Electric vehicles (EVs) have emerged as a promising solution, offering reduced greenhouse gas emissions, lower dependence on conventional fuels, and enhanced energy efficiency. However, the effective integration of renewable energy sources, reliable motor drives, and advanced power converters remains critical for the widespread adoption of EV technology.

Among various motor technologies, the Permanent Magnet Brushless DC (PMBLDC) motor has gained significant attention in EV applications due to its high efficiency, high torque-to-weight ratio, wide speed range, and low maintenance requirements. The use of sensorless control techniques further enhances system reliability and reduces cost by eliminating mechanical position sensors.

For powering EVs, solar photovoltaic (PV) systems integrated with battery storage provide a sustainable and eco-friendly energy source. However, the intermittency of solar power necessitates efficient energy management and power conditioning. In this regard, the Zeta converter plays a vital role as a versatile DC–DC converter, capable of maintaining a regulated output voltage, enabling maximum power point tracking (MPPT), and ensuring seamless charging/discharging of the battery.

Furthermore, incorporating regenerative braking in EV systems significantly improves energy efficiency by capturing kinetic energy during braking and feeding it back into the battery. This not only extends the driving range but also reduces overall power consumption.

This work presents the design and analysis of a sensorless PMBLDC motor-driven solar-PV battery-fed EV system employing a Zeta converter with regenerative braking capability. The proposed system aims to optimize energy utilization, ensure robust motor control, and enhance the reliability and sustainability of EV operation.

II. LITERATURE REVIEW

Sensorless Control Methods for BLDC Motor Drives — recent review (2025). This contemporary review compiles sensorless approaches across back-EMF sensing, model observers, and advanced estimation schemes, discussing nonidealities (asymmetric back-EMF, inverter dead-time) and practical constraints for EV drives. It highlights trends toward observer-based and hybrid solutions to cover full speed range and recommends combining estimation with robust control to reduce torque ripple and improve startup performance. This paper helps set the methodological baseline for sensorless PMBLDC systems discussed in later works.

Position and Speed Control of Brushless DC Motors Using Sensorless Methods (Gamazo-Real et al., 2010). A classical study describing early sensorless schemes including back-EMF detection and sensorless commutation for trapezoidal BLDC drives, with experimental validation. The paper is useful historically and technically for understanding how back-EMF integration and terminal-voltage methods were developed and their limitations at low speed — a recurring issue in EV regenerative scenarios.

A Review Paper on Sensor-less BLDC Motor Control (IJNRD, 2023). This mid-decade review revisits sensorless techniques with emphasis on practical implementation on embedded microcontrollers and DSP platforms, comparing detection thresholds, startup routines, and computational costs. It supports practical recommendations for low-cost EV prototypes where hardware resources are constrained.

Sensor-less Field-Oriented/Sliding Mode Control for BLDC (Ramesh et al., 2022). The authors propose a sliding-mode estimator to reconstruct back-EMF and speed, enabling field-oriented control behavior for BLDC machines. Their approach shows robustness to parameter variations and load disturbances — properties useful for EVs operating under variable road loads and partial PV supply.

Position-Sensorless Control for PMBLDCM using back-EMF methods (Singh, 2016). This work provides a complete sensorless control scheme for PMBLDC motors based on back-EMF sensing and commutation logic. It demonstrates effective commutation and torque production in simulation and experiments, useful as a template for integrating back-EMF sensorless commutation into EV motor controllers that must also manage regenerative modes.

Robust Position Sensorless Technique for a PMBLDC Motor (ResearchGate entry). Presents a robust mechanical sensorless technique tailored to PMBLDCs, addressing rotor eccentricity and parameter uncertainty. The robustness claims and the methods for handling nonidealities inform design choices when vehicle loads and motor parameters vary over time.

Integrated Zeta Converter PV-Battery System with Fuzzy-logic MPPT and Regenerative Braking in EV (2025). This paper proposes an integrated Zeta DC–DC converter paired with a fuzzy-logic MPPT and regenerative braking control strategy. The work demonstrates how a single converter topology can be used for PV MPPT, battery charging, and energy recuperation from braking, and reports simulation results showing efficiency gains when MPPT and regenerative flows are coordinated. It is directly relevant to system architectures aiming to minimize the number of power stages on small EVs.

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Zeta Converter for Electric Vehicle Battery Charger (IJIREEICE, 2024). The authors describe a Zeta converter–based battery charger topology for PV-fed EVs, highlighting the non-inverting buck–boost behavior and control methods for voltage regulation. The paper is practical in orientation and useful for designers selecting converters for on-vehicle PV charging and regenerative capture.

Synergizing Solar PV and Regenerative Braking using a Zeta Converter (RJETM, 2024). This study proposes an energy management strategy and examines how a Zeta converter can route both PV and regenerated energy to the battery while performing MPPT. It reports simulation results and discusses control priorities (MPPT vs. battery charging vs. regenerative capture) — a valuable systems perspective when integrating PV arrays on EVs. rjetm.in

Electric Vehicle Driven by Solar PV Batteries and Regenerative Brakes via a Zeta Converter (IJTSRD / IJTSRD52591). Focused on regenerative braking implementation with BLDC motors, this paper demonstrates simulation-level validation of braking energy capture routed through a Zeta converter to recharge batteries. It highlights braking control and converter management strategies applicable to small EV prototypes.

Single-stage ZETA-SEPIC converter for Plug-in Electric Vehicles (2019). Proposes a single-stage integrated converter achieving propulsion, plug-in charging and regenerative braking modes with wide voltage conversion. The single-stage philosophy reduces component count and can lower losses and cost when carefully designed, making it attractive for compact solar-assisted EVs.

Development of high-gain switched-capacitor based bi-directional converters for EVs (2024). This recent paper explores high-gain bi-directional topologies suitable for EV charging and regenerative capture; although not Zeta per se, the converter family complements Zeta-based designs when higher step-up/down ratios or improved efficiency are required. Its contributions are relevant for designers needing higher conversion ratios between PV, battery and motor/generator domains.

A Review: Sensorless Control of Brushless DC Motor (IJERT). An earlier comprehensive review that categorizes sensorless methods, startup schemes and hardware implementation notes. It's useful for grounding newer proposals and understanding the tradeoffs between simple back-EMF methods and observer-based techniques.

Luenberger-Observer Based Sensorless Control (SPIE conference paper, 2025). Introduces a discretized low-order Luenberger observer tailored for BLDC sensorless estimation with attention to digital implementation — relevant for low-compute microcontroller platforms that will run motor estimation and converter control simultaneously in an EV.

Review on Back-EMF Position Sensing Techniques (CoLab / book chapter, 2025). This review examines multiple back-EMF-based detection methods (terminal voltage, third harmonic, integration) and discusses limitations at low speed and under PWM switching. It recommends hybrid approaches (observer + back-EMF) for full-range performance, corroborating multiple practical system papers that integrate regenerative braking and PV charging.

III. PV SYSTEM

Photovoltaic Technology

The device or elements capable of transforming photons light into an electrical voltages and current energy is called photovoltaic. Electrons in photovoltaic materials are formed due to small-scale wavelength and high-energy photon, so that they are atoms free. Electrons around the electrical field will be attracted towards metallic contact where they can flow as electrical current. The driving force to power photovoltaic comes from the sun, and it is interesting to note that the total energy demand of the earth's surface takes like 6000 times more energy.

Photovoltaic began in 1839, when the Nineteen year old French physicist, Edmund Becquerel published a diluted electrolyte solution (Becquerel, 1839) on the metal electrode, voltage could be seen. Almost 40 years later, Adams and Day Solids (Adams & Day, 1876) were the first to study photovoltaic influences. They were able to create selenium-made cells that are 1% to 2% active. The emerging photography industry quickly accepted Selenium cells for photographic light meters; In fact, they still use it for the purpose [19].

$$I_d = I_0 \left(e^{\frac{qV_d}{kT}} - 1 \right)$$

Where,

I0 - Diode saturation current

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Q - Electron charge (1.602×10-16 C)
Vd - diode voltage
K - Boltzmann constant value is 1.3806×10-10 J/K

IV. MPPT ALGORITHM

For tracking the maximum power from PV system, various methods have been developed over the decade which involves simple voltage and current relations. For this research work, Incremental Conductance algorithm is chosen due to its superiority over other algorithms.

Incremental conductance

This MPP algorithm is based on the fact that at the Maximum power point, the P-V curve slope is zero. The power obtained from the PV is differentiated with respect to voltage.

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV}$$

At MPP, the rate of change of power w.r. to voltage is zero

$$\frac{dI}{dV} = -\frac{I}{V}$$

The algorithm of the Incremental Conductance works by comparing the incremental conductance ($\frac{dI}{dV}$) with instantaneous conductance ($-\frac{I}{V}$). Achieving the $\frac{dP}{dV} = 0$ is the control aim to achieve MPP of the array. Positive value of dP/dV refer that the operating region lies on the left hand side of MPPT and increase in array voltage would yield increase in power. Alternatively, negative value of dP/dV infers that the operating region had exceeded the MPPT and increase in voltage would reduce the power as shown in figure 2.11.

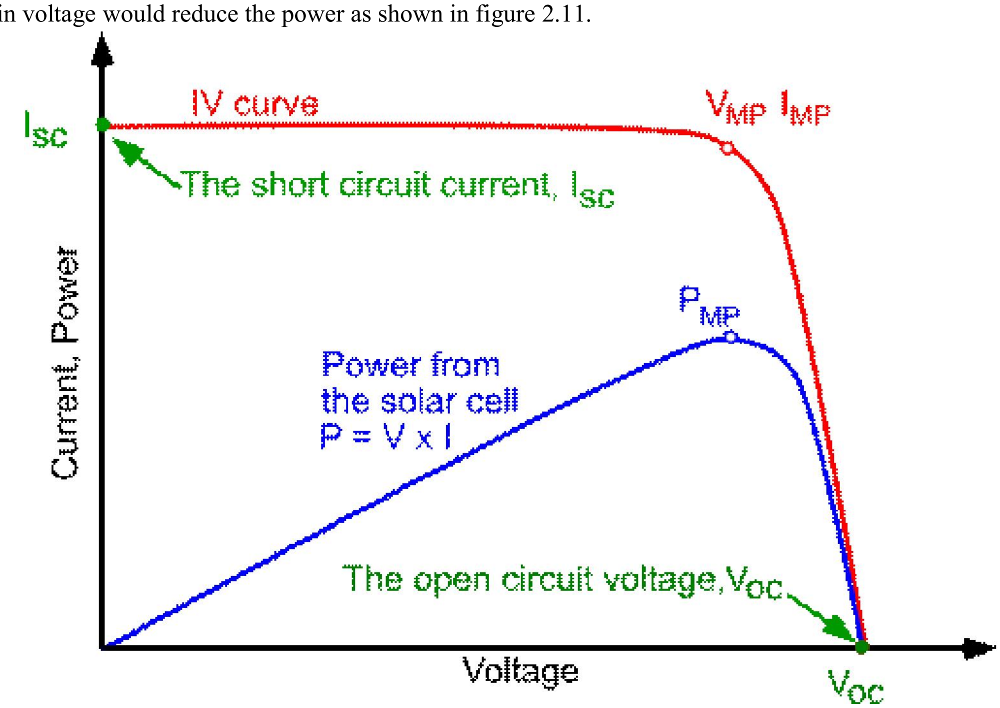

Figure 3.1 : P-V curve for IC

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V. SPEED CONTROL OF BLDC MOTOR

A BLDC motor is any of a class of electrical machines that converts direct current electrical power into mechanical power. The most common types rely on the forces produced by magnetic fields. early all types of BLDC motors have some internal mechanism, either electromechanical or electronic, to periodically change the direction of current flow in part of the motor. Most types produce rotary motion; a linear motor directly produces force and motion in a straight line.

The proposed BLDC motor drive eliminates the phase current sensors. It is desired to operate the BLDC motor-pump at its rated speed irrespective of the climatic condition. This is achieved by continuously regulating the DC bus voltage of VSI at the rated DC voltage of BLDC motor. A bi-directional power flow control enables, by regulating the DC bus voltage and hence the operating speed, to deliver a full amount of power required to pump the water with full capacity. In case the grid is not available, the DC bus voltage is not maintained at the rated DC voltage of BLDC motor under bad climatic conditions, and the speed is governed by a variable DC bus voltage.

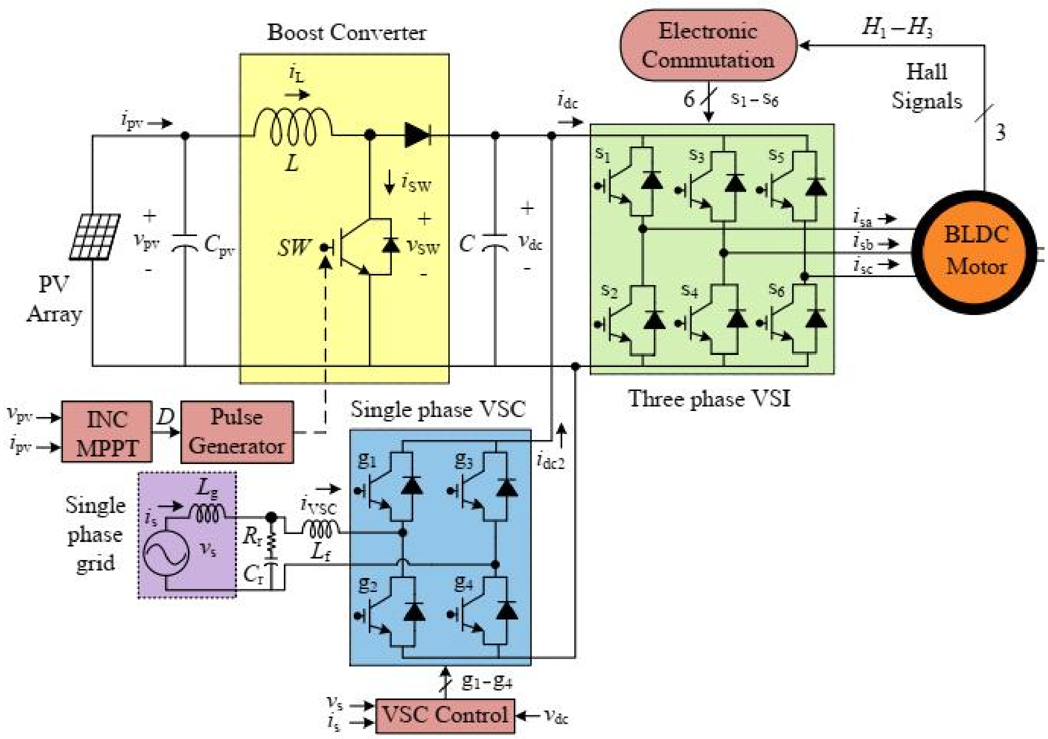

Fig. 4.1 Schematic of the grid interactive PV array using a BLDC motor drive

VI. CONCLUSION

The literature indicates promising feasibility for compact EV architectures that combine sensorless PMBLDC drives and Zeta (or similar) DC–DC converters to integrate PV charging and regenerative braking. Key advantages include reduced sensor cost, fewer power stages when single-stage or shared converters are used, and improved overall energy utilization by capturing braking energy. Persistent challenges remain: reliable low-speed rotor estimation and robust startup without position sensors; designing highly efficient, bidirectional converters optimized for both MPPT and regenerative flows; and real-world hardware demonstrations under vehicle dynamics. Future work should prioritize robust hybrid estimation that covers standstill through high speed, hardware prototypes that integrate MPPT + bidirectional converter control with the motor controller on a single embedded platform, and experimental validation on representative EV testbeds.

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