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Article Title: Renewable Energy Resources Integration for EV Applications Using Sensor less Control and Regenerative Braking

Renewable Energy Resources Integration for EV Applications Using Sensor less Control and Regenerative Braking

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ABSTRACT

This article introduces an innovative controller and motor architecture designed for an e-rickshaw powered by Renewable Energy Sources (RES). In the absence of Hall-effect sensors, brushless DC (BLDC) motor drives often experience commutation delays across both low and high speeds. Traditional control methods are limited by the small magnitude of back EMF, making them less effective. The proposed sensorless control strategy addresses this by implementing commutation error correction, enabling full-range motor operation. For cost-effective EV applications, a simple commutation error compensation technique is developed to detect freewheeling pulses, eliminating the need for low-pass filters and streamlining control. Additionally, a zero-crossing detection (ZCD) method is introduced, which corrects commutation delay without requiring a separate phase compensator. Any unwanted spikes in the ZCD circuit are removed using a fixed-delay digital filter. A modified Landsman converter is used for efficient MPPT control, delivering a smooth current output and reducing the need for a front-end ripple filter. The regenerative capability of the BLDC motor drive helps alleviate EV range anxiety, as the renewable energy source ensures a continuous power supply. A PI-based Fuzzy Logic Controller is employed, and the effectiveness of the system is validated through MATLAB/Simulink simulations.

Keywords: Battery storage, e-rickshaw, PMBLBC motor, position sensorless control, regenerative braking, solar PV Array.

1 Introduction

In India, electric rickshaws are among the most popular electric vehicles (EVs) and play a key role in the country's public transportation system. One primary challenge with these vehicles is battery capacity, which restricts their operational range. Regenerative braking, which captures the vehicle's kinetic energy and directs it back to the battery, can help mitigate this issue. By increasing the state of charge (SoC) of the battery, the energy storage can be boosted without the need for a larger, heavier, and more costly battery. The high energy density and simple control structure of Brushless DC (BLDC) motor drives make them highly attractive for EV applications. However, BLDC motors typically require six distinct rotor position

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signals, which are provided by additional signal processing circuits and three mechanical sensors installed on the stator. Unfortunately, these Hall-effect sensors can be prone to damage and reliability issues under harsh operating conditions, which raises concerns for EV usage.

To control the speed of the BLDC motor, a PI controller generates switching signals that produce PWM, while a PID controller is used for improved speed stability across various load conditions. However, commutation errors in these motors can negatively impact performance, especially at high speeds. This problem is difficult to resolve due to non-ideal factors that disrupt accurate commutation. Sensorless control, based on a third-harmonic compensation technique, addresses this issue by using virtual harmonics to minimize commutation errors, thus enhancing system performance and appeal.

For reliable performance across diverse operating conditions, the motor is connected to a drive system arrangement that includes a power converter. These power electronics converters, such as dc-dc, ac-dc, and ac-ac types, increase energy output from the source and are composed of power semiconductor elements suitable for a variety of power levels. Basic boost and buck-boost converters are commonly used to raise DC bus voltage due to their cost-effectiveness and simplicity, though they may not provide the necessary voltage gain for high step-up applications. Conventional converters tend to have significant passive components and reduced efficiency. The Landsman converter, however, overcomes these limitations with fewer required components compared to other converters like SEPIC, ZETA, and Cuk, offering a higher voltage gain with fewer issues.

Power switches in these systems are regulated using PWM, PI, and PID control, which provides the correct duty cycles to achieve the required voltage gain. Fuzzy-PID control is implemented to stabilize the system, allowing the Landsman converter to enhance DC link voltage, reduce settling time, and ensure a stable input for a three-level voltage source converter (VSC). The fuzzy-PID method is further developed using IFOC control and back EMF estimation for the BLDC motor. For a BLDC motor powered by a Landsman converter, maximum power point tracking (MPPT) with an Incremental Conductance algorithm is proposed to maximize power output from a PV system. This approach is compared with existing systems in terms of improved DC link voltage and reduced settling time, showing promising enhancements for the proposed setup.

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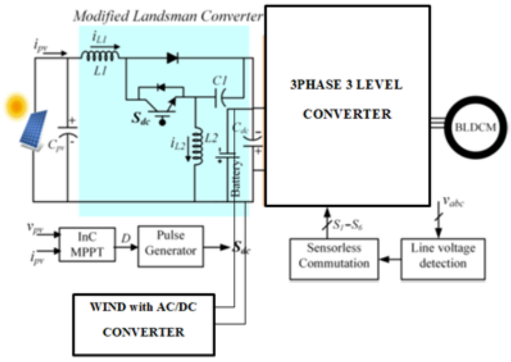

Figure 1: *Block Diagram of Proposed Converter*

2 Proposed System

In the proposed system, illustrated in Figure 1, a brushless DC (BLDC) drive is powered directly by a photovoltaic (PV) source. This design integrates a three-level Voltage Source Inverter (VSI), a Landsman converter, a single-diode PV array, a wind energy system with AC/DC conversion, and a BLDC motor. The Landsman converter enhances voltage gain, delivering it to the VSI, which is connected to the BLDC motor. The system employs a fuzzy-PID control strategy to achieve high voltage gain and optimize the output voltage settling time of the converter. Additionally, the Sensor less Control Technique is applied to regulate the BLDC motor's speed and minimize ripple, ensuring smoother operation.

3 Modelling of PV System

The photovoltaic (PV) array block is composed of numerous PV modules organized into strings. Each string consists of modules connected in series, while the strings themselves are connected in parallel to form the overall array. This PV array block utilizes a five-parameter model, which includes a current source (representing the light-generated current, IL), a diode with defined parameters (reverse saturation current, I0, and ideality factor, nI), along with series resistance (Rs) and shunt resistance (Rsh). These components are essential for modelling the I-V characteristics of the PV modules, which fluctuate based on changes in irradiance and temperature.

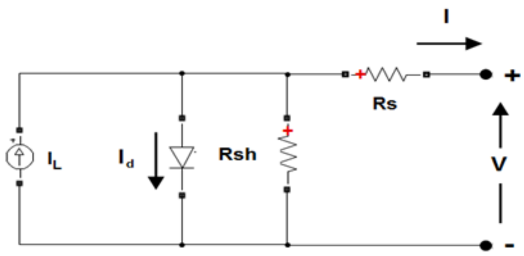

Figure 2: *Single Diagram of PV System*

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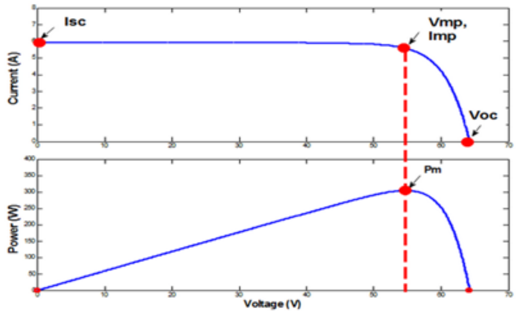

Figure 3: *PV characteristics*

The diode I-V characteristics for a single module are specified by the formulae.

$$I_d = I_0\left[\exp\left(\frac{V_d}{V_T}\right) - 1\right]$$

$$V_T = \frac{kT}{q} \times nI \times Ncell \tag{1}$$

The diode current is denoted as Id, diode voltage as D, diode saturation current as Io, ideality factor as nI, the Boltzmann constant as k, electron charge as q, cell temperature as T, and the number of cells as Ncell. A high-efficiency solar panel with a peak power of 380 W powers the electric vehicle system when connected in series. The parameters of the solar PV array and the converter are configured based on the open-circuit voltage and short-circuit current, with a chosen total open-circuit voltage of 70 V and short-circuit current of 9.36 A. Under maximum power point tracking (MPPT) conditions, the voltage across the panel reaches approximately Vmp = 47 V, and the current at this point is Imp = 380/47 A. The incremental conductance algorithm is used to achieve MPPT by setting the incremental conductance (ipv/vpv) equal to the actual conductance (ipv/vpv). The MPPT algorithm also adjusts the duty ratio of the modified Landsman converter to maintain optimal power output. A high-frequency pulse generator supplies the gate pulses necessary for the converter, and the system is planned with ideal solar insolation conditions in mind.

The buck-boost property of the enhanced Landsman converter manages the partial shade situation. Ideally, a 10% loss from partial shadowing may be prevented.

4 Designing of Landsman Converter

The LC converter is a type of DC-DC converter, operating in continuous conduction mode (CCM), and its performance depends on changes in irradiance levels. Designed to increase the power output from the photovoltaic (PV) system, the LC converter improves voltage for brushless DC (BLDC) motors, resulting in faster settling times and enhanced performance. This configuration optimizes the PV array's output voltage to ensure a stable, secure, and quieter operation for the BLDC motor. Through its operation, the LC converter effectively regulates the DC bus voltage, achieving a higher voltage gain.

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The LC converter consists of two inductors (L1, L2), a switching device (sdc), and a capacitor (C1). The input to the LC converter is connected to the PV array output, while a DC capacitor (Cdc) is connected to its output. For this system, the solar panel's current and voltage ratings are set to ipv = 8.11 A and vpv = Vmp = 47 V. Since the input inductor (L1) of the modified Landsman converter matches the rated current of the PV panel, the current through L1, or iL1, is also 8.11 A.It is anticipated that the duty ratio of the dc-dc converter would be as follows:

$$D = \frac{V_{dc}}{V_{dc} + V_{pv}} = \frac{48}{48 + 46.8} = 0.506 \quad (2)$$

where Vdc and vpv stand for the DC bus and PV panel output voltages, respectively. To find the current passing through the dc link capacitor at its maximum power, apply the following formula.

$$I_{dc} = \frac{P_{mp}}{V_{dc}} = \frac{380}{48} = 7.91A. \quad (3)$$

PWM pulses for the converter are produced at a frequency of 20 kHz. The terms IL1 and IL2 represent the inductor currents. The output voltage ripple is constrained by the large value of the dc bus capacitor, even if a little amount of ripple is permitted to flow in the circuit to determine component size. The dc bus capacitor is enhanced by using the highest and lowest angular frequencies of the VSI. The LC Converter's Parameter Design is shown in Table I.

5 PID Fuzzy Controller

Fuzzy logic uses verbal expressions to define operational rules instead of relying on mathematical formulas. In many systems, traditional methods become impractical due to their complexity, making it difficult to accurately represent them, even with advanced mathematical equations.

Fuzzy logic terms offer an effective way to describe a system's functional behavior. Fuzzy logic controllers serve as a type of symbolic controller, and in this study, the proposed PV-based DC-DC and DC-AC converters include a power switch (S) regulated by a fuzzy-PID controller. The system utilizes a three-level converter and a brushless DC motor-driven photovoltaic setup with Fuzzy-PID control to achieve a high voltage gain. Even when set points vary, this control method ensures the system reaches the desired reference values, integrating both PID controllers and fuzzy logic in its approach.

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Table 1

Parameter	Expression	Design data	Value
C_l	$\frac{D \times I_{dc}}{f_{sw} \times \Delta V_{dc}}$	D = 0.506 I_{dc}= 7.91 A V_{dc}= 48 V ΔV_{dc}=10% of V_{dc} f_{sw}=20 kHz	41.69 μF
L_l	$\frac{D \times I_{dc}}{8 \times f_{sw}^2 \times C_1 \times \Delta I_{L1}}$	D = 0.506 I_{dc}= 7.91 A f_{sw}=20 kHz I_{L1}= 8.11 A ΔI_{L1}= 5% of I_{L1} C_l=41.69 μF	73.98 μH
L_2	$\frac{D \times V_{mp}}{f_{sw} \times \Delta I_{L2}}$	D = 0.506 V_{mp}= 46.8 V f_{sw}=20 kHz I_{L2}= I_{mp} - I_{dc} ΔI_{L2}= 5% of I_{L2}	5.85 μH
C_{dc}	$\omega_h = 2 \times \pi \times f = \frac{2 \times \pi \times N_r \times P}{120}$ $\omega_l = 2 \times \pi \times f = \frac{2 \times \pi \times N \times P}{120}$ $C_h = \frac{I_{dc}}{6 \times \omega_h \times \Delta V_{dc}}$ $C_l = \frac{I_{dc}}{6 \times \omega_l \times \Delta V_{dc}}$	P=6 N_r=3000 rpm N=800 rpm I_{dc}= 7.91 A V_{dc}= 48 V ΔV_{dc}=10% of V_{dc}	C_h=306.88 μF C_l=1092.8 μF C_{dc}=1000 μF

A PID controller typically includes proportional, integral, and derivative values that help minimize oscillations and correct steady-state errors. In cases where the load and set point are variable, the proposed Fuzzy-PID controller is employed to optimize and generate switching signals for the converter's power switch. Fuzzy logic is applied to determine the parameters Kp, Ki, and Kd dynamically. The Fuzzy-PID controller uses two inputs, error and delta error, and provides three outputs, corresponding to Kp, Ki, and Kd. This design reduces settling time and enhances system stability, while the Fuzzy-PID controller also boosts the input source for the voltage source inverter.

The suggested Fuzzy-PID controller architecture block design for the dc-dc landsman converter is shown in Figure 4.

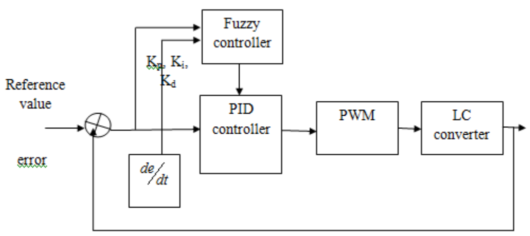

Figure 4: *Fuzzy-PID controller Block Diagram*

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The two most important aspects of designing any fuzzy system are:
1. Fuzzy rules; and
2. The selection and modification of membership functions.

A novel approach using fuzzy logic mathematics has been developed to enhance voltage, frequency, and current control in variable speed drives. This method is particularly suited for electric vehicle (EV) applications, addressing challenges where non-linearity and dynamic behavior are difficult to manage with traditional control methods. This control approach is well-suited to handle these complex system characteristics.

As shown in Fig. 5, the fuzzy logic membership functions are categorised into five groups: five MF for inputs and five MF for fuzzy sets of outputs. A Mamdani fuzzy inference system is used in this system to establish a connection between two input variables and one output variable. The two input variables are the error (e), which is the difference between the intended (set-point) and measured value, and the change of error (d), which denormalises the specific variables of a conventional control gain.

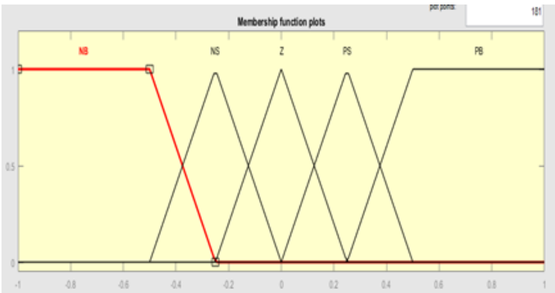

Figure 5: *Membership function of FLC*

Table 2. *Fuzzy Rules*

Δwe	we				
	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

NB, NS, Z, PS, and PB, instead of just meaning negative big, negative small, zero, positive small, and positive large, respectively, may be used to generate a more precise continuous control rule by using the fundamental table of rules' interpolation. This instance selects symmetrical triangles with equal bases and a 50% overlap with adjoining MFs, excluding two hazy groups at the outer edges (which are selected as trapezoidal MFs).

The system performance may be enhanced for EV applications by utilising this fuzzy controller in the outer loop and building the necessary control terms utilising the error signal and variation of error as input signals.

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6 Simulation Implementation

A Simulink model has been developed featuring a fuzzy-PID controller with an LC converter, where a BLDC motor is powered by a renewable photovoltaic (PV) array. To regulate the high DC link voltage, the Landsman converter is supplied with limited energy from the PV modules. The output DC voltage from the PV-fed converter is then provided to a voltage source inverter (VSI) to generate three-phase voltages required to run the BLDC motor. The primary goal of the proposed fuzzy-PID controller is to minimize settling time and effectively manage the DC link voltage response of the LC converter.Figure 6 shows how the recommended controller, which regulates the converter's response, displays the Simulink model. The MPPT is used to produce the most power achievable.

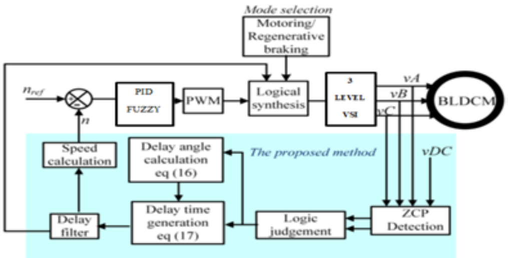

Figure 6: *Proposed Simulink Diagram*

Switching signals are generated by the Hall controller (HC) based on the assessment of the Hall effect sensor signal, which corresponds to the rotor angle needed for the drive. A sensorless back EMF approach is employed to estimate the voltage and current in the stator of the brushless DC motor, providing data that helps regulate both torque and speed in the proposed system. This method allows for accurate observation of the rotor's position and speed. The recommended cascaded multilevel inverter produces switching signals at specified levels to reduce harmonic distortion within the carrier setup, utilizing a PID-based control method.

A three-level inverter was used to produce the recommended system. Fig. 7 shows the proposed circuit's Simulink implementation. The proposed system's parameters are shown in Tables 3 and 4.

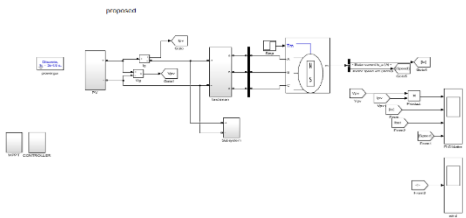

Figure 7: *Simulink Implementation of Proposed Circuit*

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Table 3: *System Parameters*

Component of drive	Value
BLDC motor	48 V, 850 W (nominal), single speed, 7:1 gear arrangement
Solar-PV array	250 W (maximum)
Battery pack	Lithium-ion, 48 V, 100 Ah
Power converters	A 2-kW modified Landsman converter and A10 kW three-phase VSI

Table 4: *BLDC Motor Specifications*

BLDC motor parameter	Value
Stator per phase resistance, (R_{ph})	0.18 Ω
Stator per phase inductance, (L)	50 mH
Motor constant (V_{peak}L-L/krpm)	33.513
Motor torque constant (Nm/Apeak)	0.32
Pole pairs	2
Inertia (kg.m^2)	0.02

7 Simulation Results

A PMBLDC motor rated at 850 W will be used to thoroughly evaluate the proposed drive design. Under different loading conditions and speeds, position sensorless control is employed. The following is a collection of the experimental results and relevant discussions.

7.1 Results of Solar PV System with MPPT Control

The input power to the drive adjusts gradually based on the level of available solar irradiation. An AC-DC converter allows the motor to be powered simultaneously by the solar panel, battery, and wind sources. As shown in Figure 8, battery power increases to maintain consistent motor speed when solar irradiation decreases, while on sunnier days, the reliance on battery power reduces due to higher solar energy availability. In both transient scenarios, motor speed remains steady. Throughout the operation, a load torque of 1.4 Nm is applied.

A comparison of converter output power with a quick load shift. A redesigned Landsman converter, with shorter ripple and faster settling periods, offers better stability.

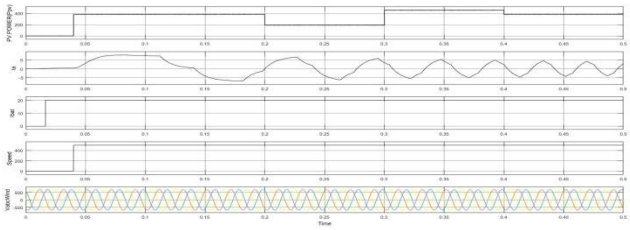

Figure 8: *PV Power, Stator Current, Battery Current Motor Speed, Wind Voltage*

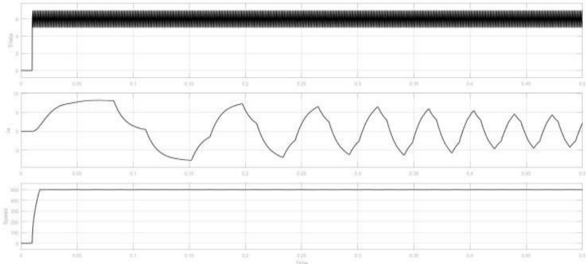

Figure 9: *Theta, IA, Speed*

7.2 BLDC Motor Drive Performance with Position Sensorless

Figure 9 illustrates the steady-state behavior of the proposed system, showing the rotor angle (theta), stator currents, and motor speed. The sensorless algorithm takes control as soon as the rotor begins to accelerate. Initially, two phases are activated using a predefined commutation strategy to position the rotor at a specified location. To provide the high starting torque needed by the electric vehicle (EV), the phase current is nearly twice the rated current. In contrast to the 400 ms acceleration time required by the LPF-based sensorless control, the proposed method transitions to sensorless operation in approximately 230 ms.

The load torque is initially adjusted at 3 Nm. The current regulation limits any surge during start-up, enabling a smooth and rapid startup.

7.3 At Different Speed Conditions

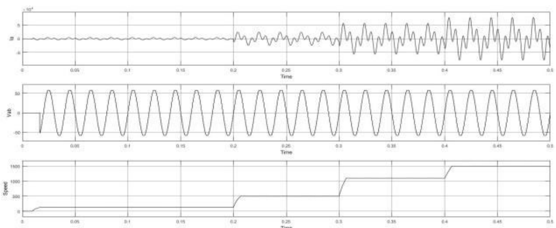

Figure 10: *Performance OF System under Different Speed Conditions at 130 rpm, 500 rpm, and 1100rpm*

Fig. 10 illustrates the effect of the proposed commutation error correcting logic on the phase current at different speeds. The suggested approach is compared to the traditional LPF-based delay compensation logic for this EV application, and a significant reduction in current ripple IA is seen. At high speeds, the current ripple utilising the method becomes more severe. This

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is the result of the flawed ZCPs. The current spike that occurs during commutation is caused by the imbalanced dc link voltage and the software's calculation delay, even if the LPF-based approach also takes this into consideration.

The proposed method controls the current ripple while maintaining the shape of the current profile. Consequently, the proposed compensation strategy reduces current spikes and improves the BLDC motor drive's sensorless commutation.

7.4 Performance under Different Load Conditions

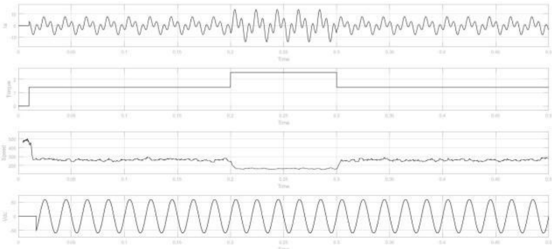

Figure 11: *Ia, Torque, Speed, Vab*

Figure 11 depicts the drive's dynamic response as the load varies. When the load reaches the rated 2.6 Nm, there is a slight decrease in speed accompanied by an increase in current. As the load is reduced to half of its torque rating, the current decreases. In both scenarios, the DC bus voltage remains stable, indicating that the speed stabilizes in equilibrium. However, during the transient phase, there are brief speed undershoots and overshoots.

8 Conclusion

This study analyzed the startup, dynamic, and steady-state performance of a proposed E-rickshaw powered by a solar PV array and driven by a BLDC motor with a Landsman converter. The use of the Landsman converter effectively minimizes current oscillations in the modules caused by snubber components, eliminating the need for external filters. The hybrid PV-wind system is designed for autonomous operation, relying entirely on renewable energy during use. The proposed system's effectiveness was validated through MATLAB SIMULINK simulations, which showed that both the solar and wind generators could charge the battery and supply energy to meet the load's requirements. In this setup, position sensorless control is achieved by monitoring the DC bus voltage and voltage levels to determine commutation points. Any variations or imbalances in the bus voltage can lead to current ripple, distorted current profiles, and incorrect commutation timing, which can negatively affect system performance.