Advanced control architectures for enhanced simulation and operational analysis of solar PV-driven vehicle systems

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Article Info

Article history:

Received Dec 24, 2024
Revised Aug 21, 2025
Accepted Oct 2, 2025

Keywords:

Advanced control strategies
Dynamic load management
Energy conversion efficiency
Maximum power point tracking
Solar photovoltaic
System reliability
Vehicle drive systems

ABSTRACT

Interplanetary interest in solar PV systems in automobiles has grown as renewable energy, especially in transportation subsystems, is used more widely. Emphasizing innovative control strategies to increase power conversion efficiency, reliability, and flexibility, this paper identifies and assesses solar photovoltaic integrated vehicle drive systems. In Simulink, several researchers replicate power systems, solar PV systems, vehicle propulsion systems, and power conversion technologies. To imitate real-world settings, researchers evaluate the efficiency of the device at many solar light and load values. High-level control techniques suitable in such unpredictable conditions are MPPT and dynamic load control. These controls are definitely required to ensure the correct functioning of the plant system, independent of natural variables, like irradiation and temperature. After that, the performance of the suggested control strategies is investigated under the main success criteria: energy analysis, system efficiency, and operational stability. This implies that solar PV integrated systems for automobiles could gain from ideal performance and durability, hence improving the off-grid operation of cars. These findings offered latent promise for use in the developing transportation sector and advancement of solar PV technology.

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1. INTRODUCTION

The increasing energy requirements worldwide, coupled with the scarcity of resources, particularly non-renewable sources, have enriched numerous research studies and increased applications of renewable energy systems. Of all the energy-intensive sectors, the transportation sector plays a considerably big role in emitting greenhouse gases [1]. However, the figures show that traditional vehicles that rely on the combustion of gasoline or diesel have remained popular. The following constant environmental and economic issues due to fossil fuels have culminated in the development of cleaner energy solutions [2]–[6].

This study is informed by the imperative to move to the use of renewable energy, especially in vehicle power systems. Renewable solar photovoltaic (PV) power solutions have been considered for their use in the automotive industry with interest. Of all the renewable resources, solar energy is one of the most potential to be harnessed to help minimize greenhouse gases and its effects on the conventional transport systems [6]-[10].

Solar photovoltaic, which uses the sun's energy to directly provide power, has, over the last few decades, undergone considerable development as a result of its mandate to provide clean energy. Originally, PV systems were installed in non-mobile contexts, namely homes and businesses, but they currently supply power that was previously drawn from the main grid. General improvements in PV technology and increased use of green energy in modern society have urged researchers and engineers to consider applying PV in mobility, especially in automobiles [11], [12].

Electricity-operated solar PV cars are more preferable to cater the energy and environmental crises of conventional vehicles. The following is the block diagram of the proposed PV-based electric vehicle system shown in Figure 1. These systems reconvert solar energy to electrical power to the electric motors, using them a lot less or not at all in relation to fossil fuels [13]. Switching to electric vehicles that run solely on solar energy could greatly decrease emissions of greenhouse gases, improve the quality of the air, and decrease the reliance on fossil energy [14], [15]. This software connects the key components that define PV-powered systems, such as the photovoltaic solar panel, the mode of vehicle movement and the power conversion modules into a single model for evaluation before deployment [16].

In the present work, MATLAB/Simulink is used to model and simulate the entire solar PV operated automobile drive system. The simulation shows how the PV array is connected to the electric motor and the processes of power conversion. In this way, while applying various conditions of solar irradiation, temperature, and load, work is evaluated the system’s performance to identify optimization potentials. Scientists also model such conditions and control strategies in order to explain the system dependability and productivity [17]-[19].

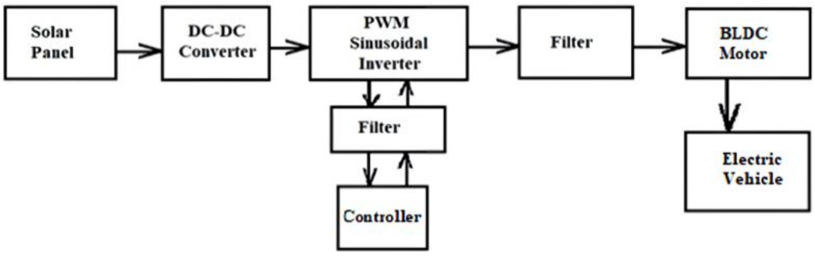

Figure 1. Fundamental block diagram of the proposed PV-based electric vehicle system

2. PROPOSED CONVERTER FOR EFFICIENT AND STABLE POWER TRANSFER

It is always likely to attain the desired voltage for either the motor or the inverter, and this can result in instability or even low performance. In an attempt to counter this, a DC-DC converter is used to either amplify or simplify the voltage. This converter makes sure that the system produces only the desired voltage levels to the subsequent stages. BLDC motor needs an AC supply; therefore, the DC produced needs to be converted using a pulse width modulation (PWM) sinusoidal inverter. This inverter produces a quasi-sinusoidal current by chopping the voltage source at a high frequency, which makes the waveform suitable for driving the motor.

2.1. The DC-DC converter circuit of the proposed work

In the latest model of the proposed system, the DC-DC converter has been provided with a power of 2000 W and an input voltage range of 12-50 V, delivering a stable 48 V output. This converter runs at 200 kHz of switching frequency using the switching elements of Insulated gate bipolar transistors (IGBTs). For high-speed switching, high current-carrying capacity, and efficiency in energy transfer, IGBTs are selected.

This converter design is especially valuable for use in electric vehicles (EVs), renewable energy systems, and industrial power systems. It works as a buck-boost converter, which gives it the ability to work with both input voltages higher and lower than the output voltage of 48 V. In the following section, the block diagrams for the converters employed in the proposed system are shown in Figure 2.

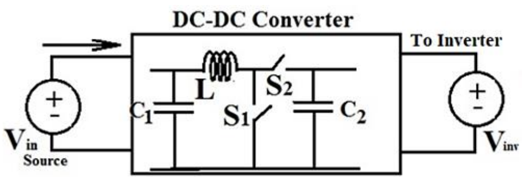

Figure 2. Basic block diagram for the converters for the work

High carrier frequency: The utilization of the 200 kHz frequency reduces ripple in the circuit to enhance power transfer and design density. Energy storage: The inductor effectively permits energy storage during the switching process due to the utilization of an IGBT with fast turn-on and turn-off times. PWM control: The converter uses PWM to control the signal and to regulate the amount of power in the output voltage. Feedback is incorporated to provide amplitude stability under varying load conditions or changes in the input signal [20], [21].

2.2. PWM inverter for smooth operation of BLDC motor

BLDC motors are used in electric vehicles such as cars since they are efficient, possess high torque, and have a long lifespan. However, they need the use of an AC source, preferably a three-phase supply, in order to achieve the required voltage. A PWM inverter is a device that is used to convert an acceptable direct current electrical power supply to an alternating current electrical power supply in the form of a waveform suitable for driving the intended motor. It does so by sequentially turning on and off power transistors such as IGBTs or MOSFETs to convert direct current voltage to the output in the form of alternating current. Switching frequency is set to 10 kHz and is controlled to generate a waveform as close to a sinusoidal AC as possible. This device is bi-modal and draws input voltages from the 48 V DC battery system in the vehicle. The main blocks of the inverter switch at a carrier frequency of 10 kHz. The sine wave required in driving the BLDC motor is approximated using pulse width modulation, as shown below. To reduce switching losses and electromagnetic interferences, the PWM controller involves varying the inverter-operating conditions [22], [23].

Advice on AINS controlling suggestions for this research. This work employs a buck-boost converter able to manage voltages above 48 V. Insulated gate bipolar transistors (IGBTs) in the converter at 200 kHz provide high current and quick switching. Focuses on adjusting output currents and voltage via pulse width modulation. For electric cars, BLDC motors are perfect because of their economy, torque, and lifespan. To lower switching losses and electromagnetic compatibility, they employed a pulse width modulator controller along with a 48 V DC input voltage.

This paper will propose a study of a DC-to-DC converter circuit. As semiconductor switches, these deliver the higher voltage value and the current from the input side of DC-DC converters and regulate voltage and current at the output side. The characteristic that constitutes the working principle of the circuit is to toggle the input voltage at very high frequencies. But the voltage waveform should first be filtered and then set in order to get the required level of the output DC voltage [24]–[26]. Output voltage (Vo) calculation:

$$V_o = V_{in} \times \frac{(1-D)}{D} \tag{1}$$

Vo represents the output voltage, which is expected after having set up a voltage divider. B Vin is the input voltage level of the specified range. D represents the duty cycle of the turning signal, which turns between the load and the feed. Duty cycle (D) calculation:

$$D = \frac{1}{(1+(V_{in}/V_o))} \tag{2}$$

Here D means the duty cycle of the switching signal ‘a variable close to zero’. The input voltage range is abbreviated by Vin, while Vo represents the output voltage required.

2.3. Revisions of the proposed BLDC Motor

The 2000 W, 3000 RPM for electric automobiles, BLDC motors are reasonably priced, robust, and precision-oriented. Its inverter choice regulates motor RPM to 3000 RPM, and its 2000 W power rating enables direct conversion of electrical energy to mechanical power. Torque and speed boost motor power. Direct brushless current motors, by nature, have high torque at low speed. BLDC motors are 85–90% efficient as they include no brushes and a permanent magnet rotor. These motors might reach efficiency by removing mechanical brushes and using electrical commutation. Up to rated speed, the PWM technology of the inverter maintains torque at the necessary level. Low thermal prop kinds of BLDC motors mean most cooling systems overlook overload. This configuration lowers motor life and requires less maintenance than brushed motors, which need. Since BLDC motors do not arc, they are fit for areas prone to sparks. With the exception of bearings and air cooling, a BLDC motor is quiet and efficient. They are excellent for electric cars, residential use, and low noise-producing health-enhancing equipment [27].

3. FOR THE PROPOSED SYSTEM, A MATLAB SIMULATION IS CONDUCTED TO EVALUATE ITS PERFORMANCE UNDER VARIOUS OPERATING CONDITIONS

To simulate a BLDC motor using MATLAB/Simulink, create a new model and the following key parameters include: stator resistance, inductance, and back electromotive force (EMF). Initialize a motor by its parameters, such as rated power, speed, stator resistance, self and mutual inductance, back EMF constant, and the number of poles. It also features a DC power supply, PWM inverter machine, BLDC motor controller, load block, as well as simulation configuration and design. Once this model is done, simulate the motor to understand how it behaves and then compare it to what has been learnt in theory. A scope or time series is one of the tools that can be utilized to display the results generated.

A BLDC motor creates a stator magnetic field electronically, without any mechanical commutation; thus, no brushes are required. This magnetic field, however, enables the permanent magnet rotor to align and thus be rotatable. Figure 3 depicts the functional block diagram for the MATLAB/Simulink mode of the proposed system. Some of the unique features include high efficiency, reliability, as well as fine speed and torque characteristics. Current representations used for BLDC motor simulations are motor models, DC supply, PWM inverter, and motor controller.

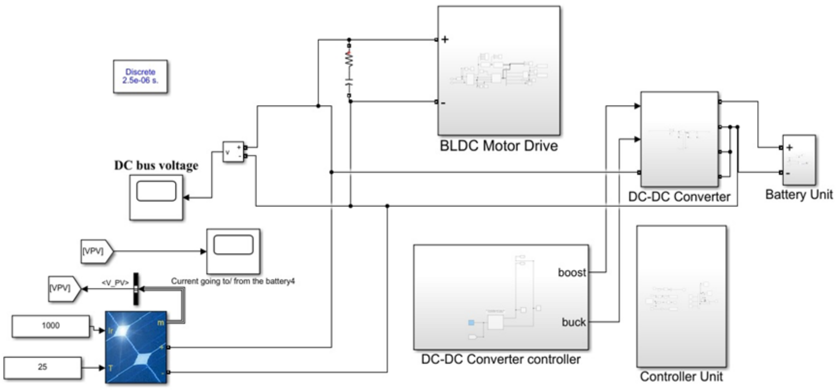

Figure 1. Functional block diagram of MATLAB/Simulink of proposed system

3.1. Key modeling parameters include

A three-phase induction motor consists essentially of the stator-connected windings, rotor motion, and the counter-electromotive force (back EMF). Critical operational characteristics impacting motor performance include power rating, angular velocity, back EMF, torque, and the applied switching logic control techniques. High-fidelity sinusoidal waveform generation is typically achieved through sinusoidal pulse-width modulation (SPWM), utilizing reference triangular waveforms in combination with subtractive modulation techniques. Using a folded triangle current waveform improves output accuracy even further.

A key performance metric, the load-carrying capacity, is primarily a function of both the power rating and rotational speed of the motor. Back EMF, intrinsically linked to rotor velocity, is directly proportional to the winding current and serves as a pivotal factor in regulating current flow within the motor. MATLAB/Simulink has extensive modeling capabilities for back EMF characteristics and may therefore be applied to assess the efficiency of flux linkage as a function of speed and electrical power.

Torque hill in the simulation takes into account speed, load, and current, with reference to both winding current and back EMF. The PWM inverter working in this process takes DC battery power and converts it to an AC source compatible with the motor – a three-phase AC signal. The modulating signal is a 10 kHz frequency, which controls the switching signals of the transistor in the inverter. The duty cycle is determined by the switching logic while the sine wave inputs for the motor are produced by SPWM.

The inverter transistors are controlled by the superimposed carrier signal and the system has a switching frequency of 10 kHz. This configuration provides needed control of the duty cycle and makes it easy to keep the system stable as the load changes. The present stream characteristics, torque plot, and speed plot in the simulation are typical of a 2000 W, 3000 RPM BLDC motor. These challenges include renewable energy driven electric vehicles that the proposed system's framework embraces to provide improved performance, energy efficiency and operational reliability. The simulation results prove useful in understanding the dynamic behavior of the motor and contribute to the development of green automobiles.

4. RESULTS AND DISCUSSION

The dynamic performance profile of the 2000 W, 3000 RPM BLDC motor is evident in the simulation results, which appear as a clear acceleration phase followed by steady operation. Motor torque response is dependent on speed and load; the current response exhibits high torque during acceleration, followed by low torque ripple common to high-frequency PWM inverter. Torque characteristics also follow typical behavior where it experiences high values during transient stages of motor starting and the lowest towards the steady-state condition. Here, the PWM inverter has high-frequency switching, which reduces the harmonic distortion and thus improves the motor performance. The likelihood of change in the motor speed, as a result of mechanical load fluctuations and transient load conditions, shows that it can easily handle changing loads. This proves the versatility of the motor and its performance under fluctuating usage conditions.

In the context of energy efficiency, the motor is extremely efficient, converting electrical energy to mechanical power, with comparatively small losses arising from back EMF and resistive winding losses. There are higher and sophisticated levels of motor control, a higher frequency PWM inverter, and optimum power utilization for improving the total performance output. Such characteristics make the motor ideal for electric vehicle use, because efficiency, durability, and flexibility are parameters essential to embracing environmental sustainability as well as to being effective in the way it operates. The simulation results thus affirm the rationale for the design of the system and provide illuminating findings that may prove useful in the utilization of renewable energy in vehicles.

4.1. The characteristics of the BLDC motor and converter

The scaled plot again illustrates that at the startup, the motor achieves a magnitude of 3000 RPM, which in fact shows the high initial torque value. Moreover, at the initial stage, an overshoot is observed. The rise and the subsequent changes for this effect in terms of the number of RPM progressively increase, and then level off around 1000 RPM as a clear demonstration of the damping mechanism of the system involved. Subsequently, the damping effect occurs to maintain steady and normal operation of the motor at close to 1000 RPM or more. Also, the plot demonstrates the torque-speed curve, where an initial maximum of 6 Nm is observed, which is characteristic of BLDC motors, but indicates the high torque demand during the initial stages. This characteristic can be seen to correlate with the behavior of a motor where a large amount of torque is needed to start the movement before the system reaches normal running conditions.

The remaining time-varying behavior specifies the ways in which the damping mechanisms of the system successfully limit the oscillations of the motor's amplitude, therefore, providing good regulation of motor performance. Figure 4 shows the typical waveforms of the BLDC motor and the DC-DC converter to distinguish their action in operation. The motor achieves nearly constant steady-state torque of 6 Nm, which shows that the performance is best regardless of the load. The graph shows the motor response during the starting up period, the immediate response, or the transient response, and the ultimate steady state response of the motor.

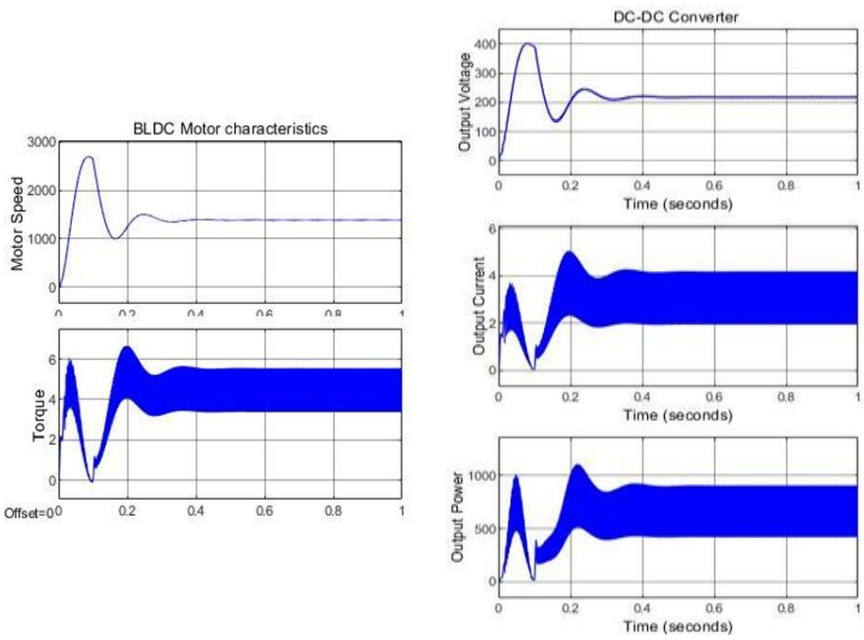

Figure 4. Characteristic wave form of BLDC motor and DC-DC converter

Also depicted is the output voltage waveform of the DC-DC converter, now operating as a buck or a boost, or a buck-boost converter are required. During start-up or when load switching, overshooting or dithering is experienced because the circuits in the converter contain inductors and capacitors as energy storage elements. The system takes nearly 0.25 sec to become stable, which shows dynamic response during start-up transient or during switching transient. The system first charges to a first-order transient value and then oscillates before settling down in the final steady state value.

The power response graph also shows the transient response of both voltage and current as they oscillate, before reaching the final constant value. There are feedback control methods, like using pulse width modulation or any other digital or analog control modes used in the DC-DC converter to control the output voltages and current. Fluctuations are observed while energy transfer is proportional in phases before attaining a steady state. DC-DC converters are normally implemented in power supplies for electronics equipment, battery charging circuits, and renewable power systems. In Figure 4, one sees a picture of a waveform representative of the DC-DC converter behavior at start-up or during Transient conditions when the converter’s energy storage components cause oscillations. Last, only after the transient result, the system takes its steady-state result stage when all the conditions become stable.

5. CONCLUSION

Integration of solar PV systems into automobiles presents strong opportunities in increasing energy density, dependability, as well as variability in the transport segment. Thus, in view of the fluctuating climate conditions, the integrated MPPT and dynamic load management system can enable high performance and control. From several of the outlined scenario analyses, it can be seen that operating reliability and performance of solar electricity-powered vehicle systems are feasible. To examine these possibilities, the work undertook simulations under different solar and load conditions. Promising solutions included off-grid vehicle applications, which enhanced the development of solar and renewable energy sources, primarily photovoltaic solar energy. This research benefits the world by increasing and implementing the option of solar photovoltaic for electricity within the constantly growing transportation industry.

FUNDING INFORMATION

The authors declare that no funding was received for this work.

AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Raghupathi Mani	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	
Susitra Dhanraj		✓		✓	✓	✓		✓	✓	✓	✓	✓		
Karthikeyan Nagarajan	✓	✓	✓		✓	✓	✓			✓	✓		✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data availability does not apply to this study, as no new data were generated or analyzed.

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