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Dynamic Performance Analysis of Hybrid System Fed BLDC Motor Drive Speed Control Using Ultra Voltage-Lift Converter

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***Abstract* - The integration of renewable energy sources into motor control systems has garnered considerable attention in recent years due to its sustainability and energy efficiency. This paper presents a performance evaluation of a solar photovoltaic (PV)-battery hybrid system used to power a Brushless DC (BLDC) motor for speed control, employing an ultra voltage-lift converter (also known as Ultra-Lift Luo Converter). The solar PV system provides a green and renewable energy source, while the battery serves as an energy storage solution for continuous operation. The ULLC is utilized for efficient power conversion and regulation, ensuring a smooth and stable voltage supply to the BLDC motor. The performance metrics, including system efficiency, speed control accuracy, and power delivery stability, are evaluated and compared under different operating conditions. Results indicate that the proposed system offers enhanced performance, demonstrating superior energy efficiency, reduced losses, and better control response compared to conventional power conversion systems.**

Keywords: Solar PV, Battery, Hybrid System, BLDC Motor, Speed Control, Ultra-Lift Luo Converter, Renewable Energy, Power Conversion, Efficiency.

I. INTRODUCTION

The increasing demand for energy-efficient and sustainable solutions has led to significant advancements in renewable energy integration, particularly in the area of motor control applications. Brushless DC (BLDC) motors, known for their high efficiency, low maintenance, and long operational life, are widely used in various applications such as electric vehicles, robotics, and industrial automation. However, the performance of these motors relies heavily on the efficiency of the power conversion systems that supply them with electricity.

Solar photovoltaic (PV) systems have emerged as a viable renewable energy source due to their abundance and sustainability. However, the intermittent nature of solar energy requires an efficient storage solution to ensure a stable and continuous power supply. To address this challenge, a hybrid system combining solar PV and battery storage can provide a reliable power source for BLDC motor applications.

An Ultra-Lift Luo Converter (ULLC) is an advanced DC-DC converter that offers high voltage gain, low ripple, and efficient energy conversion. This paper explores the use of the ULLC in a solar PV-battery hybrid system to power a BLDC motor, evaluating its performance in terms of speed control and overall system efficiency.

II. SYSTEM CONFIGURATION

2.1 Solar PV-Battery Hybrid System

The proposed system consists of three primary components: the solar photovoltaic (PV) system, the battery energy storage system (BESS), and the BLDC motor. The hybrid nature of the system allows for the use of solar energy during the day and battery power when sunlight is unavailable.

- **Solar PV System:** The PV system converts solar energy into electrical energy. A maximum power point tracking (MPPT) controller is employed to optimize the output power from the PV panels.
- **Battery Storage:** The battery stores excess energy generated by the PV system and supplies power to the BLDC motor when solar energy is insufficient. A charge controller regulates the charging and discharging processes to prevent overcharging or deep discharge, ensuring battery longevity.

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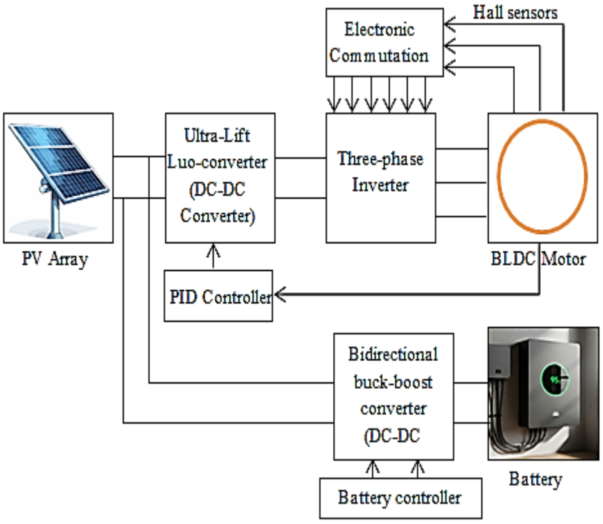

Figure 1: Proposed system configuration

- **Brushless DC (BLDC) Motor:** The BLDC motor is controlled through the proposed system, and its speed is regulated to meet the demands of the application.

2.2 Ultra-Lift Luo Converter (ULLC)

The Ultra-Lift Luo Converter (Figure 2a) is used to efficiently convert the DC voltage from the solar PV system and battery to the appropriate voltage for powering the BLDC motor.

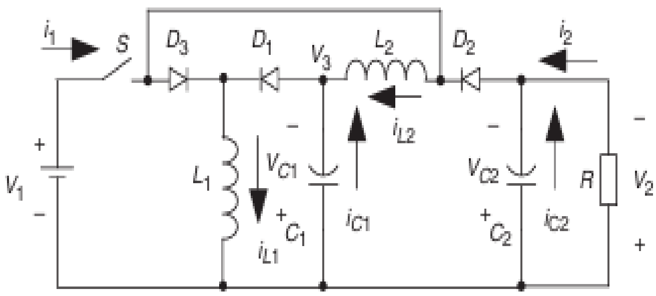

Figure 2a: Ultra-lift Luo converter Circuit diagram

The ULLC offers several advantages, such as:

- **High Voltage Gain:** The ULLC is capable of providing a higher output voltage from a lower input voltage, which is crucial for driving the BLDC motor.
- **Improved Efficiency:** The converter minimizes energy losses during conversion, enhancing the overall efficiency of the system.
- **Reduced Ripple:** The ULLC generates less ripple compared to conventional DC-DC converters, which is critical for maintaining stable motor speed and avoiding mechanical stress.

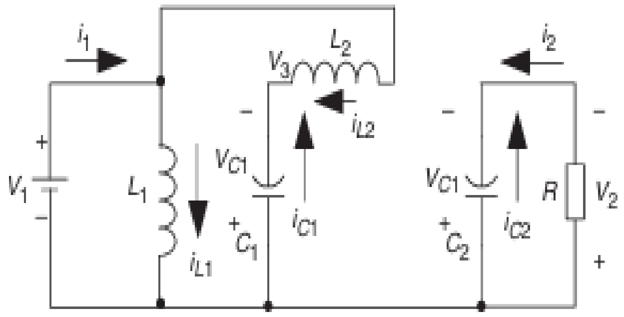

Figure 2b: Equivalent circuit during switch-on

Referring to Figs. 2b and 2c, we note that current i_{L1} increases with the slope$+V_1/L_1$ during switch-on, and decreases with the slope V_3/L_1 during switch-off. In the steady state the current increment is equal to the decrement in a whole period T.

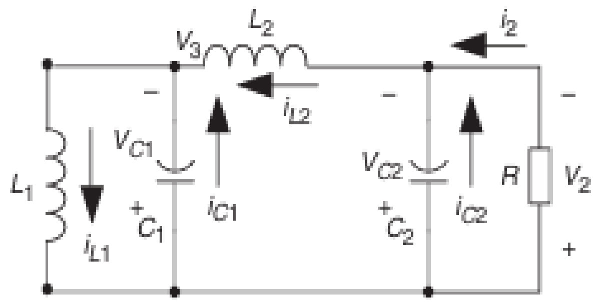

Figure 2c: Equivalent circuit during switch-off (CCM)

The current i_{L2} increases with slope$+(V_1+V_3)/L_2$ during switch-on, and decreases with the slope$-(V_3+V_2)/L_2$ during switch-off. In the steady state the current increment is equal to the decrement in a whole period T.

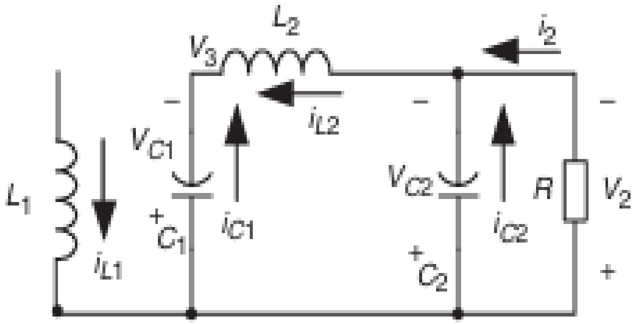

Figure 2d: Equivalent circuit during switch-off (DCM)

Referring to the Figure 2d, we can note that the current i_{L1} increases with the slope$+V_1/L_1$ during switch-on, and decreases with the slope $-V_3/L_1$ during switch-off. The inductor current i_{L1} decreases to zero before T, i.e. the current

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becomes zero before the next time that the switch turns on. The current waveform is shown in Figure 3.

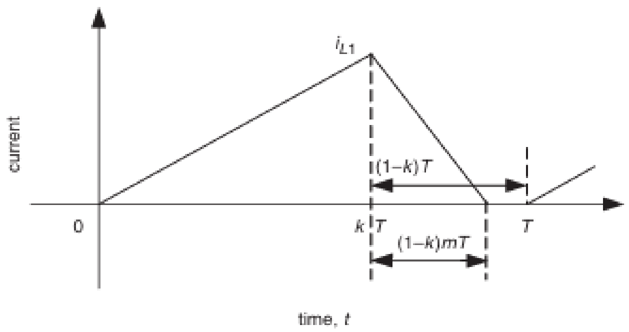

Figure 3: Discontinuous inductor current i_{L1}

Table 2: Ultra-lift Luo converter specifications

Parameter	Value
Input Voltage (V_{in})	24 – 60 V DC
Output Voltage (V_{out})	48 – 200 V DC (adjustable)
Rated Power	500 W
Maximum Output Current	5 – 10 A
Efficiency	92 – 96%
L_1	150 µH – 220 µH, 15 A
L_2	150 µH – 220 µH, 15 A
C_1	470 µF – 1000 µF, 200 V
C_2	470 µF – 1000 µF, 200 V
Switching Frequency (f_s)	100 kHz

2.3 Solar PV System

A 300 W solar PV system is a compact renewable power source designed to convert sunlight into usable electrical energy with high efficiency. It typically operates around 32 V to 40 V and produces nearly 9 A of current under standard conditions, making it suitable for charging batteries or powering small to medium DC loads. Its sturdy construction, including tempered glass and a weather-resistant frame, allows reliable outdoor operation. Due to its moderate size and stable performance, a 300 W panel is commonly used in home backup systems, standalone solar setups, and hybrid PV-battery applications.

Table 2: Standard Test Conditions: 1000 W/m², AM1.5, 25 °C

Parameter	Value
Maximum Power (P_{max})	300 W
Voltage at Maximum Power (V_{mp})	32.6 V
Current at Maximum Power (I_{mp})	9.20 A
Open Circuit Voltage (V_{oc})	39.8 V
Short Circuit Current (I_{sc})	9.70 A
Module Efficiency	18.0% – 19.2%
Power Tolerance	0 to +5 W

2.4 Battery Storage

Battery in a solar PV–battery hybrid system serves as an essential energy storage unit that ensures continuous and stable power delivery to the load, especially during periods of low solar irradiation or when sudden load variations occur. For typical BLDC motor applications, a 24 V or 48 V lithium-ion or lead-acid battery bank is commonly used due to its high energy density, longer cycle life, and reliable discharge characteristics.

The battery stores excess energy generated by the solar panel during peak sunlight hours and supplies power when the PV output drops, maintaining an uninterrupted DC link voltage for the Ultra-Lift Luo Converter. A charge controller regulates the charging and discharging process to prevent overcharging and deep discharge, thereby enhancing the battery's lifespan.

Table 3: Battery specifications

Parameter	Value
Battery Type	Lithium-ion (Li-ion)
Nominal Voltage (V_{nom})	12 V / 24 V
Capacity	20 Ah
Energy Stored	240 Wh (12 V) / 480 Wh (24 V)
Maximum Charge Voltage	14.6 V (12 V) / 29.2 V (24 V)
Cut-off Voltage	10.5 V (12 V) / 21 V (24 V)
Continuous Discharge Current	10 A
Maximum Pulse Current	30 A
Cycle Life	500–2000 cycles
Operating Temperature (Discharge)	–20 °C to +60 °C
Operating Temperature (Charge)	0 °C to +45 °C
Internal Resistance	20–50 mΩ (Li-ion)

2.5 Bidirectional converter

A bidirectional buck-boost converter (BBC) is a DC-DC converter capable of transferring power in both directions: from the battery to the load (buck mode) or from the PV/battery to charge the battery (boost mode). This topology is crucial in solar PV–battery hybrid systems because it enables charging and discharging control of the battery while maintaining a stable DC link voltage for loads such as BLDC motors.

The bidirectional operation is typically achieved using MOSFET switches arranged in an H-bridge or half-bridge configuration with a common inductor. The converter

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regulates voltage and current using PWM control in closed-loop operation, allowing safe charging, efficient energy transfer, and protection against overcurrent, overvoltage, or short circuits.

Table 4: Bidirectional buck boost converter specifications

Parameter	Value
Rated Power	250 W
Input Voltage (Vin)	24 – 48 V DC
Output Voltage (Vout)	24 – 48 V DC
Maximum Output Current	10.5 A
Switching Frequency	50 kHz – 100 kHz
Efficiency	90 – 95%
Voltage Ripple	<1% Vout
Current Ripple	<5% Iout
Inductor (L)	220 µH
Input/Output Capacitor (C)	470 µF – 1000 µF
MOSFET Switches	60 V, 15 A
Protection Features	OVP, OCP, SCP, Thermal
Operating Temperature	–20 °C to +60 °C

2.6 BLDC Motor

Brushless DC (BLDC) motors are widely used in renewable energy systems due to their high efficiency, precise speed control, and long operational life. Unlike conventional brushed DC motors, BLDC motors eliminate the mechanical commutator by using electronic commutation, which is achieved via sensors (Hall effect sensors) or sensorless control algorithms. This design reduces friction, maintenance, and energy losses, making BLDC motors ideal for applications such as solar-powered pumps, fans, and electric vehicles.

The speed of a BLDC motor is directly proportional to the applied voltage, while the torque depends on the current. Using a DC-DC converter like an Ultra-Lift Luo Converter or bidirectional buck-boost converter allows the system to maintain stable DC link voltage, ensuring consistent motor performance under fluctuating solar or battery conditions. Additionally, PWM-based motor controllers can regulate the motor speed, torque, and direction, providing high dynamic response suitable for hybrid renewable energy applications.

Table 5: BLDC motor specifications

Parameter	Value
Rated Power	500 W
Rated Voltage	48 V DC
Rated Current	12 A
Rated Speed	3000 RPM
Torque (Rated)	1.59 Nm
Peak Torque	4.0 Nm
Pole Pairs	4
Efficiency	88 – 92%
Controller Type	PWM inverter

It is a closed loop speed control system wherein the speed of the motor is sensed and compared with the reference speed. The error signal is then processed by the PID controller so that it can control the duty ratio of the ultra-lift Luo-converter with the Pulse Width Modulation (PWM) signal. This assures that the motor runs at the desired speed despite its load and supply conditions.

Ziegler–Nichols PID tuning method

Ziegler–Nichols tuning method is a heuristic PID controller tuning method. It is developed by John G. Ziegler and Nathaniel B. Nichols. The method is applied by nullifying the integral and derivative gains, then raising the proportional gain (KP) from zero until it reaches the ultimate gain (Ku) at which time the output of the control loop oscillates stably (fig 15) and consistently.

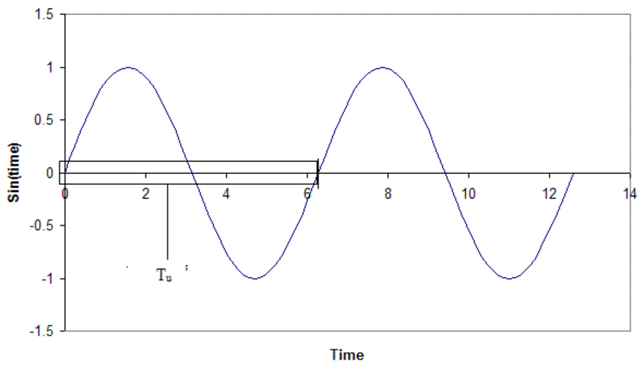

Figure 4: Calculation of oscillation period T_u

Ultimate gain K_u and the oscillation period T_u are then used to set the proportional (K_P), integral (K_I), and derivative (K_D) gains depending on the type of controller used and behaviour desired as shown in Table 6.

Table 6: Ziegler–Nichols PID tuning parameters

Controller type	K_P	T_I	K_I	T_D	K_D
P	$0.5K_u$	-	-	-	-
PI	$0.45K_u$	$0.83T_u$	$0.54*K_u/T_u$	-	-
PD	$0.8K_u$	-	-	$0.125T_u$	$0.1*k_u*T_u$
PID	$0.6K_u$	$0.5T_u$	$1.2*K_u/T_u$	$0.125T_u$	$0.075*k_u*T_u$

PID controller parameters implemented for speed control of BLDC motor are

- Proportional constant K_P=0.26
- Integral constant K_I=9.58
- Derivative constant K_D=0.049

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III. RESULTS AND DISCUSSION

The graph (Figure 5) illustrates the speed response of a Brushless DC (BLDC) motor over a time interval of 12 seconds. The x-axis represents time in seconds, while the y-axis shows the motor speed in revolutions per minute (RPM). Two curves are plotted: the reference speed, which is the desired target speed, and the actual speed, representing the motor's real-time speed.

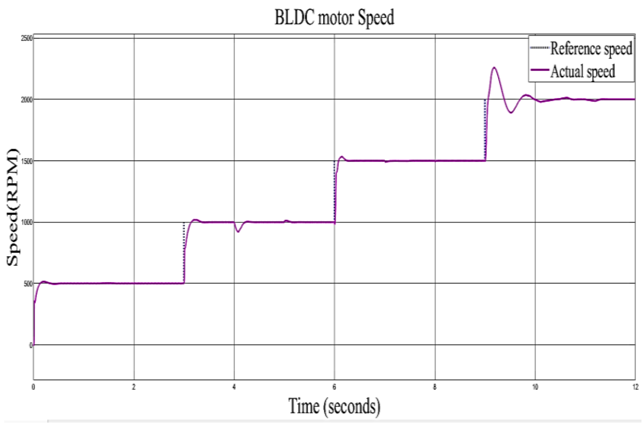

Figure 5: BLDC motor speed control

Initially, the motor speed starts at zero and gradually rises to approximately 500 RPM, closely following the reference speed. At around 3 seconds, the speed steps up to about 1000 RPM, and the actual speed quickly tracks this change with minor transient fluctuations. Subsequent speed increments occur near 6 and 9 seconds, where the reference speed increases to roughly 1500 RPM and 2200 RPM, respectively. The actual speed follows these steps with slight overshoot and settling time before stabilizing at the new reference levels.

The graph (Figure 6) depicts the input and output voltage characteristics of an ultra-lift Luo-converter over a time span of 12 seconds. The horizontal axis represents time in seconds, while the vertical axis indicates voltage in volts (V). Two curves are displayed: the input voltage and the output voltage.

At the start, the input voltage maintains a relatively steady level of about 20 V, while the output voltage is around 50 V, showing the converter’s initial boost capability. As time progresses, both voltages exhibit step-like increases at approximately 3, 6, and 9 seconds. During these intervals, the output voltage sharply rises to higher levels, reaching nearly 230 V by the 9-second mark, whereas the input voltage experiences smaller fluctuations and remains much lower in comparison.

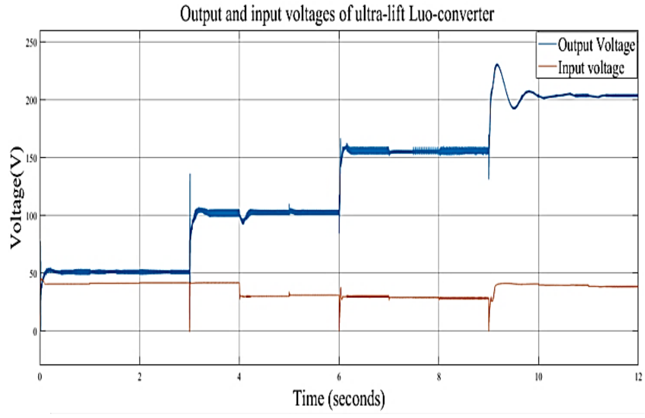

Figure 6: Ultra-lift Luo converter input and output voltages

The output voltage closely follows the step changes, albeit with some transient overshoot and minor ripples immediately after each step increase, which then stabilize quickly. These voltage changes demonstrate the ultra-lift Luo-converter's effectiveness in stepping up the input voltage to significantly higher levels with dynamic response and stability.

Simulation results show that the hybrid system successfully maintains the speed of the BLDC motor within the desired range, even during periods of low solar radiation. The ULLC proves to be highly efficient, with minimal power loss during conversion. The system exhibits stable power delivery, ensuring that the motor operates smoothly without significant fluctuations.

A comparison with traditional DC-DC converters reveals that the ULLC-based system outperforms conventional systems in terms of efficiency and ripple reduction. Furthermore, the use of a solar PV-battery hybrid system enhances the sustainability and reliability of the overall system.

IV. CONCLUSION

This study demonstrates the feasibility and advantages of using a solar PV-battery hybrid system to power a BLDC motor with speed control, employing an Ultra-Lift Luo Converter. The simulation results confirm that the proposed system offers high efficiency, stable power delivery, and precise motor speed control, making it a viable solution for renewable energy-powered motor applications. Future work could involve experimental validation of the system and further optimization of the control strategies.

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