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Design, Simulation and Experimental Evaluation of a Bidirectional Buck-Boost Converter for Low-Voltage Electric Vehicle Energy Management

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ABSTRACT—

This paper presents a non-isolated bidirectional DC–DC converter that links a 36 V battery to the DC bus of a commercial inverter feeding a 36 V, 350 W brushless DC (BLDC) motor. The power stage is a synchronous half-bridge of two IRF3205 MOSFETs with a 120 μ H inductor and a 1000 μ F bus capacitor, switched by an IR2110 driver from complementary 20 kHz signals produced by an ESP32. Since both devices are gated actively, the inductor current can change sign with no change to the hardware or gating, so one stage acts as a buck converter when motoring and as a boost converter during regeneration. In MATLAB/Simulink, flipping the load torque from +5.6 N·m to –5.6 N·m at 1 s turned the battery current from about +4.9 A into –4.9 A, and the battery state of charge, previously falling, started to rise. Currents settled in roughly 0.1 s and simulated efficiency was about 0.9 in both directions. [Add one sentence with the key measured hardware result.] The work shows that regenerative energy transfer can be demonstrated with low-cost parts and a general-purpose microcontroller.

Index Terms— bidirectional DC–DC converter, synchronous buck-boost, regenerative braking, electric vehicle, BLDC motor, ESP32, Simulink.

I. INTRODUCTION

A battery electric vehicle seldom has its battery and traction drive at the same voltage: battery terminal voltage drifts with charge level and current, while the drive prefers a stable DC link. A DC–DC converter bridges this gap. Power also has to travel in both directions, because during breaking the motor becomes a generator and its current must return to the battery instead of being burned off in friction brakes or a resistor. For this reason, bidirectional converters are widely used between storage and drive [1], [2] and also appear in charging and vehicle-to-grid systems [3].

Published designs fall into isolated types, such as the dual active bridge, which offer galvanic isolation and high gain at the price of a transformer and extra switches, and non-isolated types (half-bridge buck-boost, Ćuk, interleaved), which are compact and use fewer parts and suit moderate voltage ratios [4]. For a 36 V, 350 W drive, isolation is unnecessary and the voltage ratio is close to one, so the two-switch half-bridge is the natural choice.

Many studies of this converter either address higher power or end at simulation. Simulink models of regenerative braking such as [5] show energy flow in a battery–converter–machine chain but say little about the built system, where gate-drive supply, dead time, current sensing, switching noise and heating matter. This paper adapts the model of [5] to a half-bridge and carries the design through to an ESP32-controlled prototype. Its aims are to (i) design the converter for a 36 V battery and 350 W BLDC motor, (ii) simulate motoring and regenerative operation, (iii) generate complementary PWM with dead time on the ESP32 and drive the stage through an IR2110, and (iv) compare simulated and measured behaviour.

II. RELATED WORK AND RESEARCH GAP

Reviews compare bidirectional topologies by power rating, switching frequency, gain, component count and device stress [1], [2], [4]. Non-isolated buck-boost, Ćuk and interleaved stages are favoured for simplicity, whereas isolated bridges are used when high gain or isolation is required [4]. A plain half-bridge loses appeal at large voltage ratios, where the duty ratio nears its limits and efficiency drops [6]. In chargers the same stage steps the DC link down for grid-to-vehicle operation and the battery voltage up for vehicle-to-grid [3]. On the control side, fixed-frequency PWM with PI regulation is enough for small prototypes, while model-predictive and sliding-mode schemes aim at better dynamics [2].

Most of this literature chases new topologies, higher gain or advanced control, and pays less attention to making an ordinary half-bridge work on inexpensive hardware with a general-purpose microcontroller, bootstrap drivers and off-the-shelf sensors, which is where laboratory-scale projects meet

most of their problems. This work proposes no new topology; it documents a conventional converter and uses the simulation–hardware comparison to expose what an ideal model omits.

III. CIRCUIT AND OPERATING PRINCIPLE

As in Fig. 1, a 36 V battery with a 470 μF input capacitor feeds a half-bridge of Q1 (high side) and Q3 (low side). The switch node connects through a 120 μH inductor to a DC bus held by a 1000 μF capacitor C_o , which supplies a commercial three-phase inverter driving the BLDC motor. An ACS712 senses battery current, and a resistor divider with an LM358 buffer senses battery voltage; both go to the ESP32, which also generates the gate commands

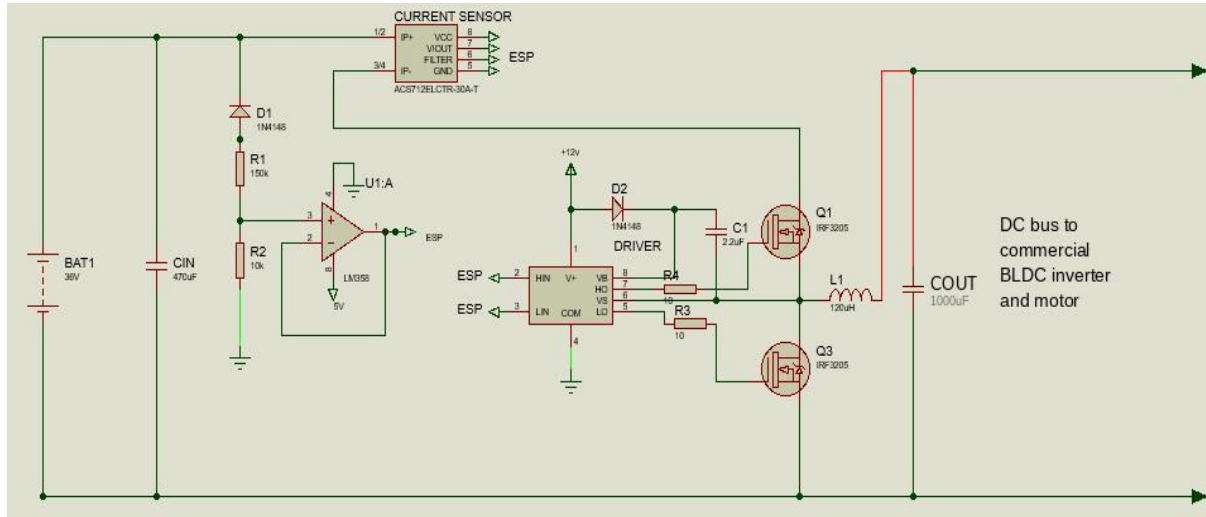


Fig. 1. Converter circuit: half-bridge, gate driver and sensing, feeding a commercial BLDC inverter.

Let V_B be the battery voltage, V_o the bus voltage, D the duty ratio of Q1 and f_s the switching frequency; Q3 is driven by the complement of Q1 with a short dead time. When motoring, Q1 is the active switch and Q3 acts as a synchronous rectifier, so the stage is a buck converter:

$$V_o = D V_B \quad (1)$$

The current ripple in the inductor L and the bus ripple (ESR neglected) are, per standard analysis [6], [7],

$$\Delta I_L = V_B D(1 - D) / (L f_s), \quad \Delta V_o \approx \Delta I_L / (8 f_s C_o) \quad (2)$$

with the ripple peaking at $V_B/(4Lf_s)$ when $D = 0.5$. In regeneration the machine delivers power and the bus current reverses; Q3 now charges the inductor from the bus and Q1 passes the energy to the battery, giving boost action $V_B = V_o/(1 - D_3)$ with $D_3 = 1 - D$, which again reduces to (1).

Power direction is therefore not chosen by the gating. At a fixed D the bus stays near $D V_B$ either way, and the machine decides the direction: motoring when its back-EMF is below the bus voltage and generating when it is above. A diode-based boost stage would enter discontinuous conduction at light load and make the gain load-dependent [6]; here the current may go negative, so conduction stays continuous and (1) holds in both directions.

With $V_B = 36 \text{ V}$, $f_s = 20 \text{ kHz}$ and $L = 120 \mu\text{H}$, the worst-case ripple is 3.75 A peak-to-peak. The rated motor current is about $350/36 \approx 9.7 \text{ A}$, so the inductor peak is near 11.6 A and its saturation rating must exceed this. The bus ripple at $D = 0.5$ is about 23 mV before ESR, and the output filter corner, $1/(2\pi\sqrt{LC_o})$, is about 460 Hz, far below f_s . The IRF3205 (55 V, about 8 m Ω [8]) gives roughly 0.8 W conduction loss per device at 10 A; its 55 V rating leaves only about 19 V of margin over the battery once switch-node ringing is included, which is the tightest limit of the design. Table I lists the parameters.

TABLE I

Design parameters of the prototype

Parameter	Value
Battery / motor	36 V nominal; 36 V, 350 W BLDC with commercial inverter ($\approx 9.7 \text{ A}$)
Switching frequency	20 kHz, complementary with dead time
L, C_{IN}, C_o	120 μH , 470 μF , 1000 μF

Parameter	Value
Switches / driver	IRF3205 / IR2110 (1N4148 bootstrap diode, 2.2 μ F, 10 Ω gate resistors)
Sensing	ACS712ELCTR-30A-T; 150 k Ω / 10 k Ω divider with LM358 buffer
Controller	ESP32 (MCPWM peripheral)

IV. SIMULATION

The model (Fig. 2) uses Simscape Electrical blocks and follows [5] with three changes: a two-switch half-bridge replaces the H-bridge, a 36 V, 10 Ah battery block supplies state of charge (SOC), current and voltage, and a step-changing torque source loads the machine. A pulse generator drives S1 and its inverse drives S2, so the switches are strictly complementary. The torque is $+5.6 \text{ N}\cdot\text{m}$ until $t = 1 \text{ s}$, so the machine motors, and $-5.6 \text{ N}\cdot\text{m}$ afterwards, so the shaft is driven and the machine generates, standing in for braking. Dead time is not modelled, the load is a DC machine rather than a BLDC drive (similar first-order behaviour: torque $\propto$ current, back-EMF $\propto$ speed), and the duty ratio is fixed (open loop).

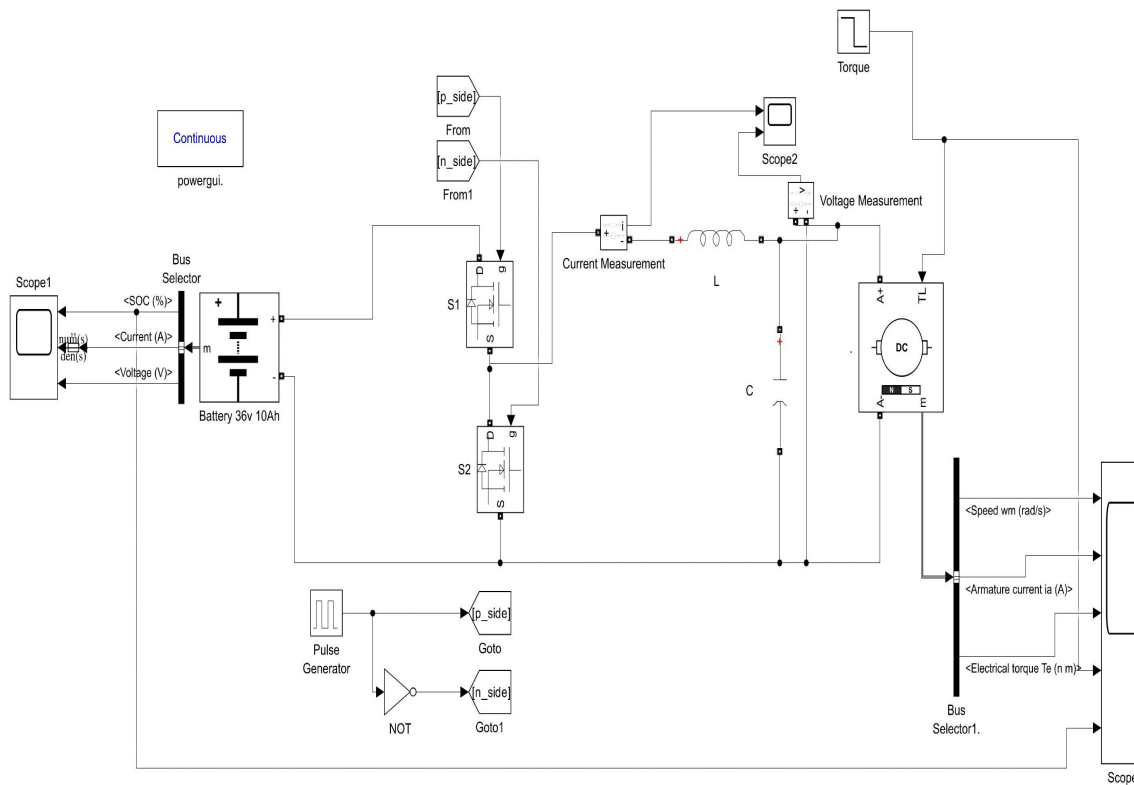
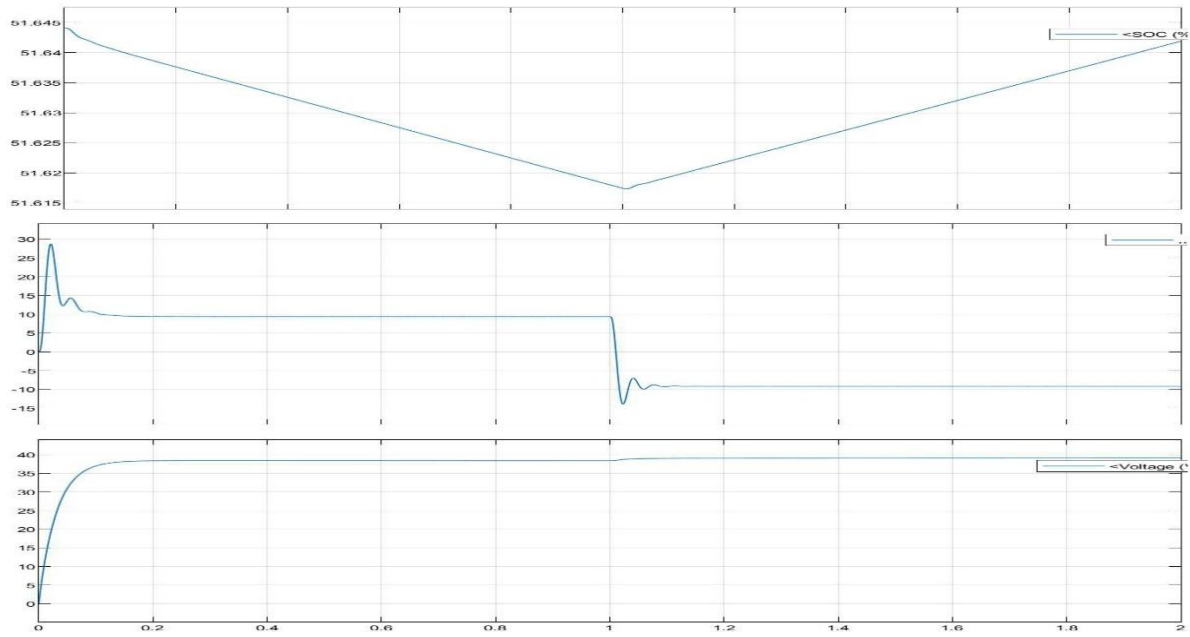


Fig. 2. Simulink model of the half-bridge, battery, machine load and logging blocks.

Battery side (Fig. 3). In the first second the battery supplies about 4.9 A at around 38.5 V and SOC drops from 51.644 % to about 51.630 %, matching the 4.9 A·s of charge removed from a 10 Ah (36 000 A·s) cell, i.e. 0.0136 %. After the reversal the current changes sign (briefly reaching about -7.5 A before settling near -4.9 A), the voltage rises by about 0.5 V, and SOC climbs at the earlier rate to roughly 51.643 % at 2 s. The small absolute change reflects only the 2 s window; the slope reversal is what shows charge returning to the battery. The first 0.15 s of the voltage trace is an initialisation transient.



Machine side. The machine reaches about 30 rad/s within 0.15 s, with a start-up armature current peak near 24 A (steady value 10 A). After the reversal, torque and armature current follow the load step to $-5.6 \text{ N}\cdot\text{m}$ and about -10 A (excursion to about -17 A). Speed rises to roughly 37.5 rad/s, as expected: with the same terminal voltage, the back-EMF must exceed it by $I_a R_a$ when generating but sit below it by the same amount when motoring. In motoring the armature current is about twice the battery current, as $I_B = D I_a$ predicts for $D \approx 0.5$. Efficiency, defined as $\eta_f = |T_e \omega| / (V_B I_B)$ forward and $\eta_r = V_B |I_B| / |T_e \omega|$ in reverse, is about 0.89 and 0.91 (Table II), so roughly 10 % is lost either way, through armature resistance and switch on-resistance. The 24 A and -17 A transients far exceed the 9.7 A rating, so a real drive needs soft-start and current limiting.

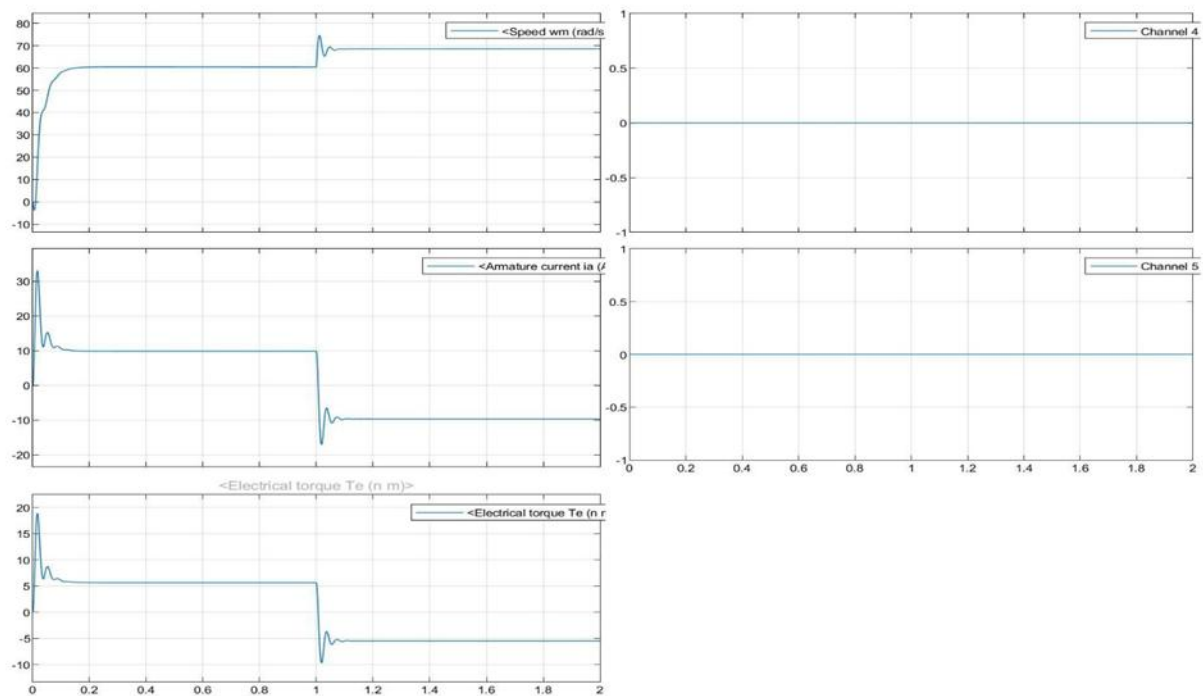
TABLE II

Quantity	0–1 s, motoring (buck)	1–2 s, regeneration (boost)
Load torque ($\text{N}\cdot\text{m}$)	+5.6	–5.6
Electromagnetic torque ($\text{N}\cdot\text{m}$)	≈ 5.6	≈ -5.5
Speed (rad/s)	≈ 60	≈ 68.5
Armature current I_a (A)	≈ 9.8	≈ -9.7
Battery current I_B (A)	≈ 10	≈ -10
Battery voltage V_B (V)	≈ 38.5	≈ 39
Peak transient of I_a (A)	33 (start-up)	–17
Peak transient of T_e ($\text{N}\cdot\text{m}$)	19 (start-up)	–9.7
Settling time (s)	≈ 0.15	≈ 0.12

Motoring performance of the bidirectional buck-boost converter-fed DC drive

The figure shows the speed, armature current and electromagnetic torque of the motor under the bidirectional buck-boost converter. During motoring (0 to 1 s), the speed rises smoothly from standstill and settles at about 60 rad/s within roughly 0.15 s. The armature current and torque show a short starting transient, peaking at about 33 A and 19 $\text{N}\cdot\text{m}$, then settle to steady values of about 10 A and 5.6 $\text{N}\cdot\text{m}$, which shows power flowing from the source to the motor. At $t = 1 \text{ s}$, a step change makes the armature current and torque reverse to about -10 A and $-5.5 \text{ N}\cdot\text{m}$ after a brief damped

oscillation, while the speed settles to a new steady value of about 68.5 rad/s. This negative current and torque indicate that the converter has moved to reverse (regenerative) power flow, so the converter handles both motoring and regeneration with fast settling and no sustained oscillations.



Parameter	Starting transient (0 to 0.2 s)	Steady state before step (0.2 to 1 s)	Transient at t = 1 s	Steady state after step (1.2 to 2 s)
Speed, ω_m (rad/s)	Rises from 0, reaching ~60	~60.3	Peaks at ~74.5, then settles	~68.5
Armature current, I_a (A)	Peak ~33	~9.8	Dips to ~-17, then settles	~-9.7
Electromagnetic torque, T_e (N·m)	Peak ~19	~5.6	Dips to ~-9.7, then settles	~-5.5
Settling time (s)	~0.15	n/a	~0.12	n/a
Power flow direction	Source to motor	Source to motor (motoring)	Reversal	Motor to source (regenerative)

V. HARDWARE IMPLEMENTATION

The prototype is built on perforated boards (Fig. 4). The control board holds the ESP32, an OLED readout, the ACS712 module, the LM358 buffer, two step-down modules for auxiliary rails, and the heatsinked half-bridge with its driver; the BLDC inverter is a commercial unit and was not built here. [Describe the second board in Fig. 4.]

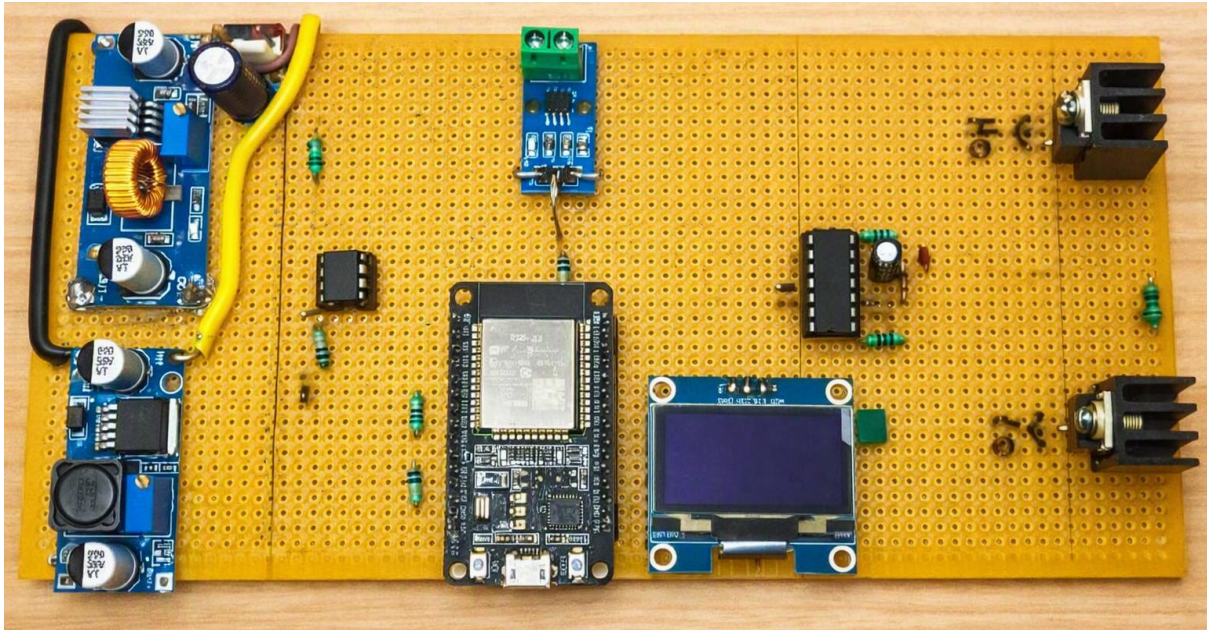


Fig. 3. Hardware prototype on perforated board of Bidirectional Buck-Boost Converter

Gate drive. The IR2110 high-side channel runs from a 12 V rail through a 1N4148 and a 2.2 μF bootstrap capacitor, with 10 Ω gate resistors. The IR2110 has no built-in shoot-through protection [9], so the controller must supply dead time of about 0.5–1 μs , longer than the MOSFET turn-off time [state value used: 10 μs]. With a gate charge up to 146 nC [8], the bootstrap droop is about $Q_g/C_B \approx 66$ mV. Because the bootstrap capacitor refreshes only while Q3 is on, the high-side duty must stay below 100 %.

Control. The ESP32 motor-control PWM (MCPWM) peripheral [11] creates one complementary pair at 20 kHz with hardware dead time, so frequency and complementarity do not depend on CPU load. Results are taken open loop at fixed duty; the sensing channels are installed for later closed-loop control.

Sensing. The ACS712 (2.5 V zero-current output, 66 mV/A on 5 V [10]) is bipolar, so charge and discharge appear on opposite sides of 2.5 V. Positioned after C_{IN} , it sees the pulsed high-side current, so the ESP32 must average over whole switching periods, and the output must be kept within the 3.3 V ADC range, a divider of two 10 k Ω resistors (1:2) halves the sensor output, so the zero-current level of 2.5 V reads as 1.25 V and the sensitivity becomes 33 mV/A at the ADC input. Battery voltage passes a 150 k Ω / 10 k Ω divider (1:16) and the LM358 buffer [12], so 36 V reads as 2.25 V; since the ESP32 ADC is noisy and non-linear near its limits, readings need averaging and calibration against a reference meter.

VI. EXPERIMENTAL RESULTS

Table 3 lists the readings measured on the prototype. At no load the motor ran at 410 rpm and drew 5.65 A from the 39.12 V supply, an input power of 221 W. On load the speed fell slightly to 400 rpm, and the current and input power rose to 8.27 A and 323 W at 39.10 V. In a regeneration test lasting about 2 s, the motor at 300 rpm delivered 3.8 A at 15 V, about 57 W.

TABLE III

Table 3. Measured hardware results of the prototype

Condition	Battery / bus voltage (V)	Speed (rpm)	Speed (rad/s)	Current (A)	Power (W)
No load (motoring)	39.12	410	42.9	5.65	221
On load (motoring)	39.10	400	41.9	8.27	323
Regeneration (about 2 s)	15	300	31.4	3.8	57

Power is the product of the measured voltage and current (39.12 V $\times$ 5.65 A = 221 W; 39.10 V $\times$ 8.27 A = 323 W; 15 V $\times$ 3.8 A = 57 W). Speed in rad/s is rpm $\times$ $2\pi/60$.

VII. SIMULATION VERSUS HARDWARE

The simulation is a best case, and the following effects are absent from it. **Dead time:** during the gap the inductor current flows through a MOSFET body diode (≈ 1 V drop), costing about $1 \text{ V} \times 10 \text{ A} \times 2 \mu\text{s} \times 20 \text{ kHz} \approx 0.4 \text{ W}$ and shifting the effective duty ratio. **Parasitic:** inductor resistance and saturation, capacitor ESR and perforated-board wiring lower the bus voltage under load and add loss. **Ringings:** layout inductance rings with MOSFET capacitance at each edge, which should be checked on the oscilloscope against the 55 V rating. **Load and measurement:** the prototype uses a BLDC motor whose commutation ripples the bus, and the ADC and pulsed-current sensing add error. Once measured, the bus voltage, battery current and efficiency should be set against Table II and differences attributed to these causes.

VIII. CONCLUSION

A non-isolated bidirectional converter for a 36 V, 350 W BLDC drive was designed, simulated and built on a synchronous half-bridge controlled by an ESP32. Simulation shows that, with fixed complementary gating, power direction simply follows the sign of the load torque: the battery current moved from about +10 A to about -10 A, SOC reversed its trend, and the transients settled within about 0.15 s. On the prototype, the motor ran at 410 rpm at no load, drawing 5.65 A at 39.12 V (221 W). Under load it ran at 400 rpm and drew 8.27 A at 39.10 V (323 W). A regeneration test lasting about 2 s at 300 rpm gave 3.8 A at 15 V, about 57 W, showing that power flows back from the motor through the converter. The prototype also highlighted issues the model hides: dead time with an interlock-free driver, the device voltage margin, and the range and averaging needs of the sensors. The tests were run open loop, and efficiency was not measured. Future work includes efficiency measurement in both directions with a known mechanical load, battery-side measurements during regeneration, closed-loop PI control of bus voltage and battery current, soft-start and over-current/over-voltage protection, a low-inductance PCB layout and a battery model fitted to the real pack.

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