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EXPERIMENTAL STUDY ON THE RATIO BETWEEN DC INPUT CURRENT AND PWM PHASE CURRENT FOR 6X6 ALL-WHEEL ROBOTIC PLATFORMS

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Abstract: *The paper analyzes the dynamics of current distribution in the propulsion system of a 6x6 land vehicle powered at 48V. The main objective is to determine the experimental correlation between the battery's direct current and the phase current (IRMS) in various load regimes.*
Using a dedicated test bench and native acquisition instruments, the study monitors the variation of current as a function of speed and PWM duty cycle.
The results provide critical data for optimizing energy management and sizing power components in complex robotic systems. The conclusions validate the integrated digital monitoring methodology, forming the basis for the development of accurate models for calculating autonomy and optimizing electrical protections according to the specific running mode.
Keywords: *6x6 UGV, DC direct current, PWM phase current, 48V Li-Ion battery, test stand, RMS current analysis.*

1. INTRODUCTION

1.1 Actual stage of research

In the last decade, Unmanned Ground Vehicles (UGVs) have moved from being mere laboratory prototypes to becoming essential tools in sectors such as industrial logistics, precision agriculture, and search and rescue or military missions. This evolution is supported by advances in energy storage and high-efficiency electric propulsion systems. According to the literature, multi-motor architectures, especially 6x6, offer superior traction and redundancy on rough terrain, but bring complex challenges in managing power flows and electrical stability [1].

Current research in the field of unmanned ground vehicles with a 6x6 configuration has focused primarily on optimizing kinematics and trajectory planning algorithms in off-road environments [8]. Although 48V electric propulsion architectures are increasingly used due to their efficient power-to-safety ratio, the literature often treats the power system as an ideal component in simulations [9]. Most published studies analyze overall energy efficiency using simplified mathematical models, without detailing the dynamic behavior of the current at critical points in the energy conversion system. Thus, there is limited documentation of the interdependence between PWM (Pulse Width Modulation) control parameters and the actual electrical response of motors under variable load conditions.

1.2 Problem description

The main challenge in designing complex 6x6 robotic systems is the precise management of current flows between the storage unit (Li-Ion batteries) and traction inverters. Currently, designers face a lack of experimental data correlating the direct current (DC) absorbed from the source with the phase current (I_{RMS}) delivered to the motors in transient modes. This uncertainty often leads to oversizing of protection components or, conversely, to thermal vulnerabilities of controllers [10]. Without an empirical model to explain how the PWM duty cycle influences current distribution at 48V voltages, optimizing the autonomy and reliability of the propulsion system remains a task based on theoretical estimates, which are often inaccurate in real field conditions.

1.3 Test procedure

Motivated by these trends, we initiated the development of our own prototype of a 6x6 ground drone, based on a 48V power supply network. The choice of this voltage was dictated by the need to balance the power required by the motors with the dimensions of the conductors, reducing thermal losses [2]. In the initial phase of the project, the main objective was to validate the constructive solution at the maximum desired load. The aim was to verify the operation mode of a permanent magnet synchronous motor, coupled to a mechanical transmission at different speed thresholds, simulating operating conditions at maximum capacity, as illustrated in Fig. 1.

During these experimental tests, carried out using a test bench and monitored by software applications provided by PWM controller suppliers, it was found that the direct current values supplied by a group of batteries showed significant discrepancies with the PWM phase currents values reported at the motor level [3]. This discovery shifted the research interest from structural resistance to the phenomenological analysis of energy conversion between source and load, a phenomenon that is the basis of this work.



Fig. 1. Illustration from the initial checks (Author's own conception)

2. INSTRUMENTATION AND TEST STAND CREATION

2.1 Propulsion and transmission system architecture

To investigate the relationship between the electrical parameters of the source and those of the electric motor, a dedicated test stand was created, capable of simulating the working conditions under maximum load for a segment of the 6x6 platform. The objective of the configuration was to isolate the behavior of a traction subassembly (front axle, left side) in order to obtain experimental data on the power flow in the circuit.

The power system consists of a configuration that uses two Li-ion battery units as an electrical energy source, providing a nominal voltage of 48V and a maximum current of 150A per unit. The energy source powers a permanent magnet synchronous electric motor. The mechanical transmission is achieved through a complex power flow: the motor is directly coupled to a precision planetary reducer, with a transmission ratio of 15:1. The output of the reducer is connected via a planetary adapted according to the model made to a wheel hub from a Dacia Duster vehicle.

The final element of the running system is an airless tire. This technological solution eliminates the risk of tire punctures and provides a constant ground footprint, essential for maintaining the accuracy of current recordings. under variable load, since the elastic deformation of the polyurethane spokes of the wheel directly influences the rolling resistance on the roller stand [4], [6].

2.2 Test procedure

The validation of electrical and mechanical performances was carried out through a procedure structured in successive phases, designed to guarantee the stability of the system and the accuracy of the collected data.

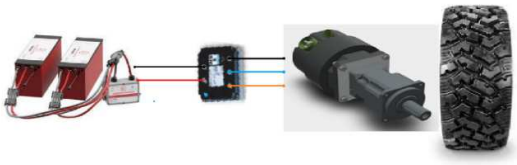


Fig. 2. Illustration of the propulsion and transmission system architecture (Author's own conception)

The first step was to position the axle segment (axle 1, left side) on a test rig fitted with metal rollers. These rollers were designed to allow the airless wheel to rotate freely, simulating driving conditions without requiring the entire chassis to physically move.

Given the high torque provided by the permanent magnet synchronous motor, the assembly was anchored using industrial fastening straps. This safety measure was taken to neutralize

reaction forces and prevent any parasitic oscillation or accidental movement of the stand during sudden accelerations or when reaching maximum speeds.

The entire test assembly was placed on a weighing platform. Before applying external forces, a tare setting (zeroing) operation was performed. This process allowed the self-weight of the components (motor, reducer, wheel) to be isolated, so that the instrument would indicate exclusively the additional vertical force that was to be applied to simulate the load on the vehicle.

To replicate full load operating conditions, an excavator arm was used as an external hydraulic actuator. The arm was positioned on the upper end of the shock absorber attachment point, exerting a progressive downward pressure. This method allowed for fine control over the applied force. The pressure was increased until the scale indicated a stable value of 320 kg, representing the maximum nominal mass calculated for each support point of the 6x6 drone.

Once the 320 kg load was established, the running process was initiated at different speed thresholds. At each operating point, the system was allowed to reach a steady state, at which point the parameters were recorded through the native software applications. Synchronized monitoring indicated the variations in the battery current I_{DC} and the phase current I_{RMS} reported by the controllers, capturing the differences in electric flux resulting from the interaction between the resistive mechanical torque and the PWM modulation system [5].



Fig. 3. Illustration of the test stand (Author's own conception)

3. RECORDED RESULTS

After stabilizing the static load of 320 kg per wheel, the experimental procedure moved to the dynamic regime analysis phase. The purpose of this stage was to evaluate the response of the electrical system under conditions of constant traction and controlled angular velocity.

We proceeded to progressively accelerate the permanent magnet synchronous electric motor speed until reaching the reference speed of 1000 rpm. The use of linear acceleration was necessary to avoid transient overcurrent that could have corrupted the nominal consumption data. Once the 1000 rpm threshold was reached, the speed was maintained constant via the PWM controller control loop, thus ensuring the system entered a stationary operating mode.

At this operating point, the command-and-control applications indicated the parameters of interest for the test procedure, namely I_{DC} from the batteries and I_{RMS} from the electric motor. After stabilizing the speed, the indicated values are found in Fig. 4.

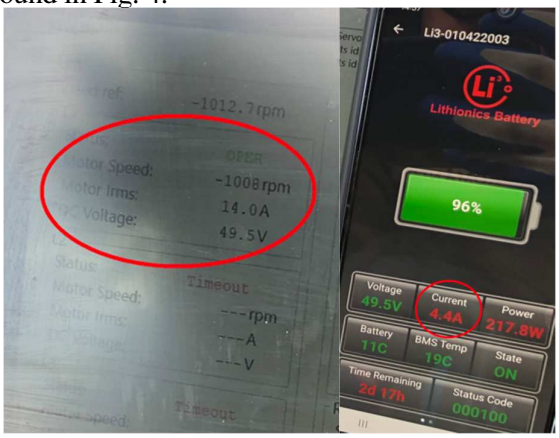


Fig. 4: Real-time current values at stable speed of 1000 rpm (Author's own conception)

After completing data acquisition for the 1000 rpm regime, we increased the speed to observe the evolution of the current values at a higher operating point, closer to the nominal travel regime of the 6x6 drone.

We proceeded to the controlled acceleration of the system from 1000 rpm to the threshold of 3000 rpm. This transition was carefully monitored to observe the mechanical stability of the wheel under the vertical load of 320 kg, considering the increased centrifugal forces. Once the speed of 3000 rpm was reached, the system was maintained

in stationary mode for a sufficiently long-time interval so that the current values had as small variations as possible, thus providing approximately constant data.

A close approximation of the values of the I_{DC} currents from the batteries and I_{RMS} from the electric motor is observed. At this operating point, the values indicated by the control applications and such as I_{DC} from the batteries and I_{RMS} from the electric motor are found in Fig. 5. The final stage was to increase the engine speed from 3000 rpm to an upper threshold of 4000 rpm, maintaining a constant vertical load of 320 kg applied through the hydraulic arm. This phase was designed to observe the behavior of the power electronics under conditions of maximum mechanical and electrical stress.

A particularly important experimental observation, recorded through telemetry provided by the monitoring applications, was the change in the ratio between the battery current and the phase current. Unlike the lower regimes (1000 and 3000 rpm), at the speed of 4000 rpm a convergence of the values was observed: the direct current absorbed from the batteries I_{DC} and the effective value of the phase current I_{RMS} presented very close values.



Fig. 5: Real-time current values at stable speed of 3000 rpm (Author's own conception)

This quasi-equality of the steady-state currents at high speed can be explained by reaching a high Duty Cycle (nearly 100%). In this state, the PWM controller no longer functions as a stressed buck converter but tends to directly transfer the battery voltage to the motor windings.

This operating mode provides relevant information for understanding the efficiency map of the 6x6 drone, suggesting that, at high speeds, the conversion losses in the controller are reduced, and the relationship between the power supply consumption and the motor load becomes almost unitary.

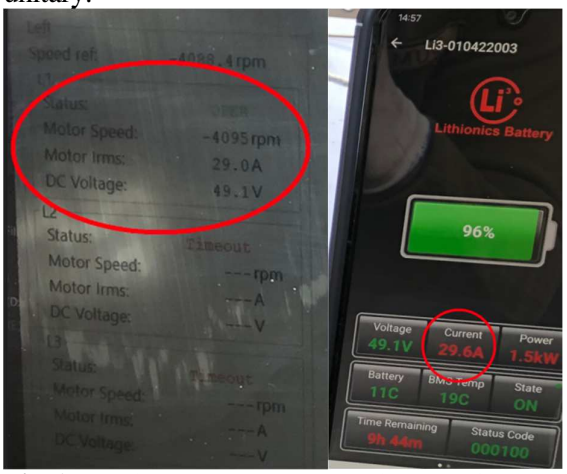


Fig. 6: Real-time current values at stable speed of 4000 rpm (Author's own conception)

At this operating point, the values indicated by the control applications and such as I_{DC} from the batteries and I_{RMS} from the electric motor are found in Fig. 6.

4. ANALYSIS AND INTERPRETATION OF RESULTS

4.1 Theoretical analysis of current transformation

The behavior of the propulsion system can be modeled in terms of energy conservation in a static Buck converter. In steady-state mode, neglecting switching losses for a simplified analysis, the relationship between input and output power is defined by:

$$\text{Pin} \approx \text{Pout} \quad (1)$$

Which leads to the formula:

$$\text{Ubat} \times \text{IDC} \approx \text{Umot} \times \text{IRMS} \quad (2)$$

where U_{mot} is the average voltage applied to the motor, determined by the duty cycle (D):

$$\text{Umot} = \text{D} \times \text{Ubat}. \quad (3)$$

This energy equality explains why, at reduced output voltages, the current in the motor phases must increase to maintain power balance. [2]

This analysis demonstrates that, as the speed increases, the controller ceases to function as a current transformer, moving towards a direct power transfer regime [2].

4.2 Analysis of current transformations from experimental data

The collected experimental data indicate a specific dynamic of the current flows, highlighting an inverse proportion between the current difference (I_{RMS} vs. I_{DC}) and the motor speed. At the 1000 rpm threshold, where an I_{RMS} phase current of 14A was recorded compared to an I_{DC} input current of only 4.4A, a transformation ratio of approximately 3.18 is observed. As the speed increases towards 3000 rpm, the ratio decreases (21A vs. 17.1A), so that at 4000 rpm the values converge almost to unity (29A vs. 29.6A).

This major discrepancy at low speeds and their equalization at high speeds is explained by the operating principle of the PWM controller, which acts on the motor as a buck converter (voltage reducer). At low speeds, to maintain the speed of 1000 rpm under the load of 320 kg, the controller applies a low average voltage to the motor terminals by reducing the duty cycle (D). [3] Since the input power:

$$Pin = Ubat \div Idc \quad (4)$$

must be equal to the output power plus losses:

$$Pout = Umot \div IRMS \quad (5)$$

the decrease in output voltage forces the current in the motor phases to increase in order to generate the torque necessary to overcome the rolling resistance of the wheel [3]. Basically, the controller "exchanges" the high battery voltage (48V) for a higher phase current, allowing the motor to develop torque without overloading the battery with direct current [2].

As the speed increases towards 4000 rpm, the back electromotive force (BEMF) generated by the motor increases proportionally, requiring an increasing supply voltage from the controller to maintain rotation. To provide this voltage, the controller progressively increases the Duty Cycle towards the maximum value ($D \approx 1$). In this "full throttle" regime, the power transistors remain open for most of the switching period, creating an almost direct connection between the 48V battery and the motor windings. Consequently, the impedance transformation disappears and the current absorbed from the source (I_{DC}) becomes practically equal to the phase current (I_{RMS}), minus the tiny switching losses and Joule effect in the conductors [7].

This convergence at 4000 rpm demonstrates that the 6x6 drone's propulsion system reaches its point of maximum direct power transfer efficiency at high rpm. At the same time, the analysis highlights the risk of underestimating the thermal load on the motor at low rpm: an operator who only monitors the battery current (4.4A) could ignore the fact that the motor windings are being driven by three times as much current (14A), risking insulation degradation without the DC line protections being activated.

5. CONCLUSIONS

The experimental study presented confirms the complexity of energy flows within 48V electric propulsion systems for 6x6 robotic platforms. The work demonstrated that the use of a dedicated test stand, together with monitoring tools provided by suppliers, is essential for understanding power conversion phenomena under maximum load conditions (320 kg/wheel).

It has been demonstrated that at low speeds (1000 rpm), the ratio between I_{RMS} and I_{DC} is maximum (14A versus 4.4A), confirming the role of the PWM controller as a step-down converter (Buck).

At the 4000 RPM threshold, the current values tend to converge (29A vs 29.6A), indicating a high Duty Cycle and a direct transfer of energy from the battery to the motor, a point at which the system reaches maximum conversion efficiency.

The significant current differences observed emphasize the need to monitor the I_{RMS} value for thermal protection of motors, as the I_{DC} battery current can severely underestimate the actual winding stress at low speeds.

As a future research direction, we aim to optimize the data acquisition process by implementing specialized analysis software, capable of generating high-resolution graphical representations for an extended range of transient and steady-state regimes.

The central objective will be to process these data sets to derive a mathematical relationship between the DC current (I_{DC}) and the phase current (I_{RMS}). Establishing this analytical model will allow for the precise estimation of the thermal demands of the motors depending on the source consumption, facilitating the implementation of advanced energy management algorithms on 6x6 robotic platforms and helping to establish autonomy in the electric mode.

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Studiu experimental asupra raportului dintre curentul continuu de intrare și curentul de fază PWM pentru platforme robotice cu tracțiune integrală 6x6

Abstract: Lucrarea analizează dinamica distribuției curentului în sistemul de propulsie al unui vehicul terestru 6x6 alimentat la 48V. Obiectivul central vizează determinarea corelației experimentale între curentul continuu al bateriei și curentul de fază (IRMS) în diverse regimuri de sarcină. Utilizând un stand de testare dedicat și instrumente de achiziție native, studiul monitorizează variația curentului în funcție de turație și factorul de umplere PWM. Rezultatele oferă date critice pentru optimizarea managementului energetic și dimensionarea componentelor de forță în sisteme robotice complexe. Concluziile validează metodologia de monitorizare digitală integrată, constituind fundamentul pentru dezvoltarea unor modele precise de calcul al autonomiei și eficientizarea protecțiilor electrice în funcție de regimul de rulare specific.

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