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Conception of an electric propulsion system for a 9 kW electric tractor suitable for family farming

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Abstract: This study presents an updated review of the application of electric tractors. A customised drive system for the conception of a novel low-power electric tractor suitable for family farms is also introduced and discussed. The introduced system comprises several aspects regarding energy generation, transmission, conversion, storage, utilisation, conservation, and management, as well as sustainability issues. A 9 kW prototype composed of two three-phase induction motors, two independent inverters, and a lead–acid battery bank is presented. Flexible and safe operation is ensured by using an electronic control unit specifically designed for this project, as a dedicated control algorithm is also developed to provide greater versatility under common rural activities. Also, a supervisory system is proposed for data storage and performance analysis. To verify the proper performance of the electric tractor, the methodology used for conducting drawbar tests has been based on document CODE 2 by Organisation for Economic Co-operation and Development (OECD). Experimental results are presented and discussed; thus, demonstrating that the proposed electric tractor is technically feasible in terms of performance when compared with a similar internal combustion engine one.

1 Introduction

Family farming stands out as one of the fastest-growing segments of food production, being of great importance to food security in many places around the world. It has also been a great ally to sustainability and socio-environmental responsibility [1, 2]. Family farms represent most of the farm systems globally, whose sizes vary from 1 to 10,000 ha [3]. In Brazil, the average size of family farms is estimated at 18 ha. It is also worth mentioning that smallholder agriculture is a complementary activity to large-scale farming, being extremely important in developing countries, where it leads to the creation of jobs in rural areas and increase of families' income [3].

Large farms typically have abundant resources available to invest in equipment, novel technologies, and employees to increase productivity. However, this is not the case of small farms, which should rely on effective government policies for this purpose. In this scenario, the appropriate agricultural mechanisation is an imminent necessity [4].

Tractors have been one of the most important tools associated with modern agriculture. Considering the need to further reduce the greenhouse gas emissions and the eventual scarce availability of fossil fuels shortly, electric tractors have been proposed by many manufacturers as a possible solution in the context of more sustainable farming [5]. However, most commercial equipment consists of high-power machines, which are only feasible to large-size properties. In fact, low-power tractors based on electric propulsion systems are not easily found either in the market or even in the literature, being this a prominent research topic that can contribute significantly to the development of family farming [6].

The development of power trains for urban electric vehicle (EVs) has been the focus of many works available in the literature. For instance, an analytical model comprising of the electrical and mechanical systems of an EV is proposed in [7]. The powertrain is composed of a battery pack, an energy management system, a direct current (DC)–DC converter, a DC–AC inverter, and permanent-magnet synchronous motor associated with a control system, as well as power transmissions, axial shaft, and wheels. The performance is thoroughly investigated and compared with that of a conventional internal combustion engine (ICE) vehicle in terms of carbon dioxide emissions while considering distinct scenarios for the generation of electricity; thus, showing that this is the prominent solution for the increase of energy efficiency.

A methodology for the modelling and design of an electric powertrain considering electromagnetic, mechanical, and thermal aspects of the required components is introduced in [8], but the conclusions are only supported by theoretical remarks and not results obtained in field tests. An energy management strategy for a dual motor-driven electric powertrain is also investigated in [9], where it is effectively demonstrated that the driving cycle influences the performance, design, and control of EV powertrains directly. Once again, experimental results are not presented and discussed.

Although there are several studies dedicated to the analysis of urban EVs, only a few works are effectively focused on the performance analysis of electric tractors. A review on the state-of-the-art of electric propulsion systems applied to tractors and agricultural machinery is presented in [10]. It is evidenced that the use of electric machine drives leads to increased energy efficiency while also bringing versatility to rural activities. The authors also mention that the Agricultural Industry Electronics Foundation developed the ISO11783 (ISObus) standard in 2002 to promote compatible communications between the tractor and implements of any manufacturer.

The application of EVs in rural areas is also described in [11]. According to Magalhães *et al.*, few patents related to agricultural tractors employing electric propulsion systems were requested over the last 30 years. Even though there is a growing concern to find alternatives to replace conventional ICE tractors with electric counterparts, this aspect is still incipient; thus, justifying the need for additional research effort in this field. Besides, among the prototypes described in Table 1, there is no design approach focused on a propulsion system based on the use of two three-phase induction motors operated by an electronic control unit (ECU) and two low-power inverter drives, being this configuration

Table 1 Brief summary of electric tractor designs

Authors	Traction motors	Motor type	Power, kW
Rodrigues *et al.* [12]	1	AC induction motor or DC motor	2.2
Chen *et al.* [13]	1	BLDC motor	7.5
Gay *et al.* [14]	1	AC induction motor	10
Escorts Group [15]	1	AC induction motor	19
Seo *et al.* [16]	1	permanent-magnet synchronous motor	20
FENDT [17]	1	—	50
New Holland [18]	1	—	100
Liu *et al.* [19]	1	BLDC motor	130
John Deere [20]	1	—	150

more compatible with the development of family farming activities.

The work in [21] addresses the operational feasibility of agricultural tractors powered by electricity. The performed study is based on the development of a small-scale prototype of EVs rated at 40 W using a DC motor. Besides, the introduction of a theoretical configuration for the electric tractor using a single electric motor is analysed. However, a detailed analysis of the motor drive and control system associated with the electric tractor is not presented, as well as the performance evaluation of a real scale prototype. On the other hand, the performance of a micro-tractor is investigated in [12] using three different types of motors: a three-phase alternating current (AC) motor rated at 2.2 kW, 220 Vac, and 3465 rpm; a DC motor rated at 2.2 kW, 36 Vdc, and 2900 rpm; and an ICE rated at 2.6 kW and 3600 rpm.

The driving performance of an electric tractor is assessed in [1], where a single 10 kW three-phase AC electric motor is used to replace 10 kW ICE in an experimental prototype. Similarly, a 20 kW permanent-magnet synchronous motor is employed in the design for an electric tractor in [16] based on the output characteristics of a conventional tractor. However, the analysis is limited to the design of the engine and experimental results with the effective application of the motor to drive a tractor are not presented to demonstrate the claimed advantages.

A control system approach for a medium-power hybrid electric tractor based on a controller area network (CAN) bus is introduced in [22], where the study is essentially focused on hardware and software developments. Several ECUs are employed, each one of them for a specific subsystem connected to a CAN bus.

A drive control system for an electric tractor prototype using a brushless DC motor (BLDC) with a nominal voltage of 72 V and a rated power of 7.5 kW is proposed in [13]. The dual-loop proportional–integral–derivative control comprising of an external speed control loop and internal current loop combined with pulse-width modulation control is adopted as the motor drive control strategy. The motor controller is designed based on field programmable gate array (FPGA), where the hardware consists of NI myRIO used as the control core while integrating ARM® to the Xilinx FPGA. LabVIEW is used as the development environment for the control system.

Another research found in the recent literature is the design of a load torque control strategy to improve the energy conversion efficiency of the 130 kW BLDC motor for an electric tractor, which can be pure electric or hybrid as described in [19]. The study comprises of mathematical modelling and performance analysis using simulation.

The possibility to integrate renewable energy sources associated with the use of electric tractors in family farming activities is suggested in [6]. Considering that the electric tractor is supposed to operate during 15 h/day and a total of 1000 h/year on average, the energy surplus that is not eventually extracted from the battery bank can be used in applications or even injected into the grid. It is also worth mentioning that the study carried out in [6] is limited to a theoretical analysis.

It is reasonable to state that major challenges for the popularisation of electric tractors include the development of novel control strategies to improve driving flexibility, manoeuvrability, and energy management, as well as the evolution of technology associated with electric machine drives, power electronic converters, and energy storage devices, while also taking into account the minimisation of cost. Within this context, this work aims to propose a customised drive system for the conception of a 9 kW electric tractor with two independent traction wheels, being compatible with family farming. The remainder of this work is organised as follows: Section 2 presents the proposed 9 kW electric tractor. Section 3 describes the experimental results of tests carried out with the electric tractor. Finally, the conclusive remarks are given in Section 4.

2 Proposed 9 kW electric tractor

From the literature review, it was found that research related to propulsion systems applied to electric tractors and the respective performance analyses are not well-discussed in the existing works. A propulsion system with two independent traction wheels and a dedicated ECU specially designed for a small-sized electric tractor have not yet been developed considering the existing approaches summarised in Table 1. In this context, it is evident that there are few propositions that specifically meet the needs of small farmers in terms of small and low-power electric tractors, being this a literature gap that must be properly explored.

According to a research developed by the Department of Agricultural Engineering of the Federal University of Ceará in Brazil, rated power of 6.3 kW is sufficient for most equipment compatible with family farming [23]. Consequently, low-power electric tractors become a viable alternative for small-sized properties, being capable of providing significant improvements and contributing to sustainability through the use of renewable energy sources [24–26]. In this context, family farms also provide great potential for micro-generation [6].

It is also worth mentioning that EVs are much more effective than their ICE-based counterparts and may even be supplied by clean energy sources [27–29]. One of the most important differences in terms of performance is the torque and speed characteristics of the electric motor [14]. Another prominent characteristic of the electric motor is the torque reserve, which is significant to achieve improved traction performance. During a limited time interval, it is possible to generate a maximum torque that exceeds the rated torque by a high factor, i.e. three or more times. In this context, the electric tractor becomes a feasible alternative to contribute to a significant improvement of family farming activities.

The propulsion system, which is specially designed for a low-power electric tractor capable of providing driving flexibility and controlling the wheel slip, has not been previously reported in the literature, being this the main contribution of this work. Prominent advantages of the proposed approach are zero carbon emissions, low noise level, high efficiency due to the use of electric motors, and low operation and maintenance costs.

2.1 Electronic architecture

The design of the electric tractor prototype represented in Fig. 1 shows the result of a comprehensive validation process involving integrated applications of mechanical, electrical, and agricultural engineering. A configuration featuring two electric motors, where each one of them is dedicated to driving a distinct wheel, has been found to meet improved requirements of robustness and simplicity. Besides, it provides great flexibility in the tractor operation since it allows the driver to control the speed and torque of each wheel independently [30].

A rear-wheel traction model is adopted in this work, where the tractor is seen as a rigid body whose lateral movement is not taken into account. Considering only longitudinal motion, Fig. 2 shows the forces acting on the moving electric tractor. Since agricultural tractors often operate at low speeds, the aerodynamic resistance can be neglected as a consequence. The resulting force associated with the interaction of the wheel and the soil is called the drawbar

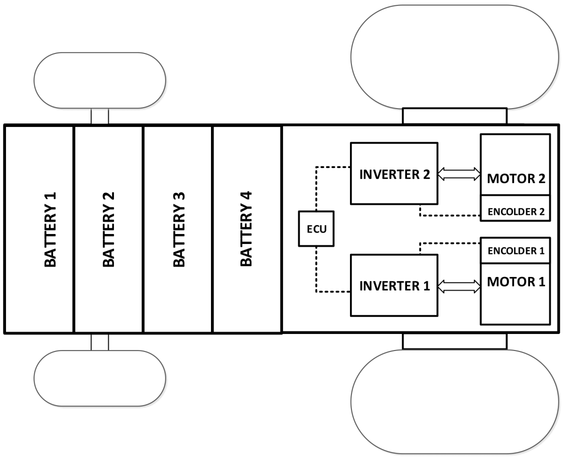

Fig. 1 *Simplified architecture of the electric tractor prototype*

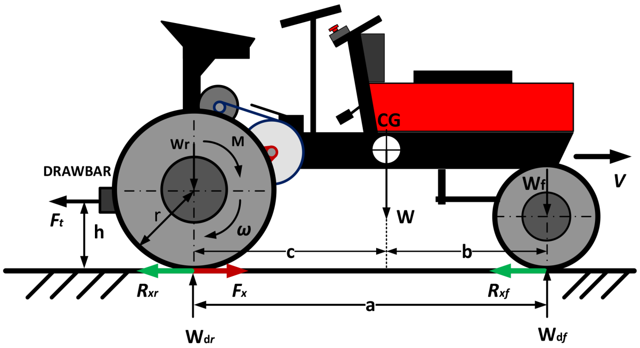

Fig. 2 *Acting forces on the tractor*

force. The electric tractor presents a complex wheel–soil interaction, as the dynamic load on the axles and the wheel model must be included in the following expressions:

$$m\dot{V} = F_x - F_t - R_r \quad (1)$$

$$R_r = R_{xf} + R_{xr} = C_r W_{df} + C_r W_{dr} \quad (2)$$

$$W_{df} = \frac{-h(F_t + m\dot{V}) + cW}{a} \quad (3)$$

$$W_{dr} = \frac{h(F_t + m\dot{V}) + bW}{a} \quad (4)$$

where m is the tractor mass; $\dot{V}$ is the tractor velocity; F_x is the longitudinal traction force of the wheels; F_t is the drawbar force; R_r is the rolling resistance; R_{xf} is the front-wheel rolling resistance; R_{xr} is the rear-wheel rolling resistance; C_r is the rolling coefficient of the tires; W_{df} is the front-wheel dynamic load; W_{dr} is the rear-wheel dynamic load; a is the distance between axles; b is the distance from the gravity centre to the front axle; and c is the distance from the gravity centre to the rear axle.

The longitudinal wheel slip λ in the model represented in Fig. 2 is given by

$$\lambda = \frac{V_w - V}{V_w} \quad (5)$$

being the traction wheel speed given by

$$V_w = r\omega \quad (6)$$

where r and ω are the wheel radius and angular speed, respectively.

The electric layout is based on the association of batteries, inverters, and electric motors. A lead–acid battery bank composed of four units is used, whose cost is less than that regarding lithium (Li)-ion counterparts, being this an important issue for the development of a cost-competitive prototype. Each battery is rated at 12 V with coulometric capacity of 200 Ah at 25°C and C/10 rate (10 h discharge rate); discharge current of 20 A; energy capacity of 217 Wh; and cut-off voltage of 10.5 V. Each battery weighs 60.3 kg, being this is an important aspect considering that the bank acts as a counterweight to provide adequate weight distribution. The series connection of the batteries provides the input voltage of 48 V to two inverters. Electric motors and inverters are manufactured by the Brazilian company WEG. Besides, the rated power of each motor is 4.5 kW, as indicated in Fig. 3.

Aiming at proper weight distribution, the motors are placed above the rear axle, just below the driver seat, while the batteries are mounted in the front section and directly attached to the chassis. This arrangement results in weight distribution of 40.9–59.1% (front–rear axle). The drive train design comprises of a simple dual chain transmission with a total transmission ratio of 34.6. Thus, considering that the rated rotational speed of the motors is 1715 rpm, the maximum rotational speed of the wheels is 49.5 rpm.

The overall dimensions of the proposed prototype are:

- wheelbase: 1700 mm;
- overall width: 1400 mm;
- overall length: 2000 mm;
- overall height (driver not included): 1100 mm; and
- ground clearance: 280 mm.

2.2 Propulsion system

The propulsion system of EVs consists basically of electric motors, power electronic converters, and ECUs. In this scenario, the study of novel control strategies and energy management technologies is necessary to provide maximum performance and autonomy [31]. For instance, the development of power electronics has led to a significant reduction in costs associated with AC motor drives. Relevant advances in this field include the development of power semiconductors capable of operating at a wide range of currents,

Three-phase induction motor - cage rotor		Inverter CVW300	
Power	4.5 kW	Rated input voltage	24-72 V_{DC}
Rated current	115 A	Rated current	200 A
Rated voltage	34 V	Peak output current (2 min)	400 A
Rated speed	1,715 rpm	Output voltage	$V_{DC}/\sqrt{2}$
Rated torque	25.1 Nm		
Maximum torque	330%		

Fig. 3 *Parameters of electric motors and inverters*

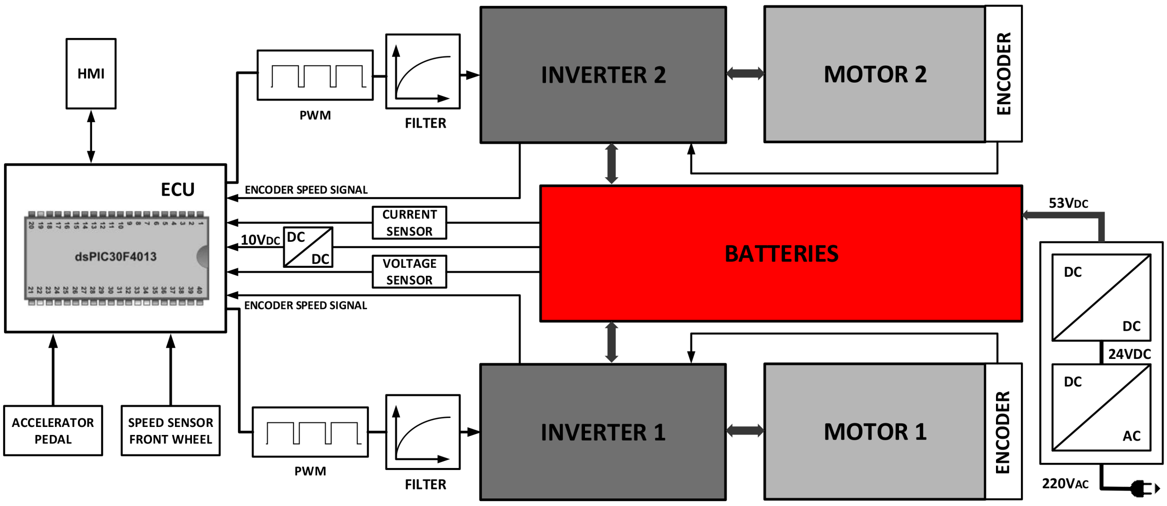

Fig. 4 *Electric propulsion system architecture*

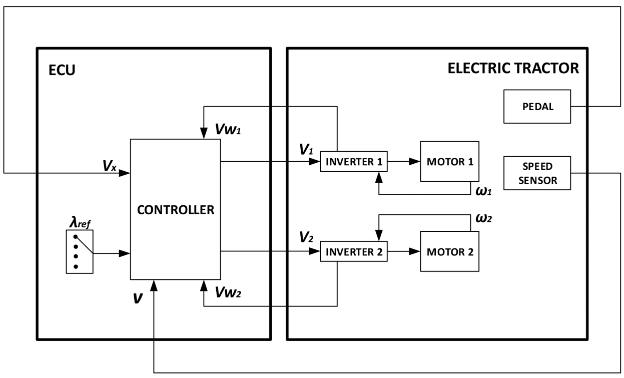

Fig. 5 *Block diagram of the electric tractor drive control system*

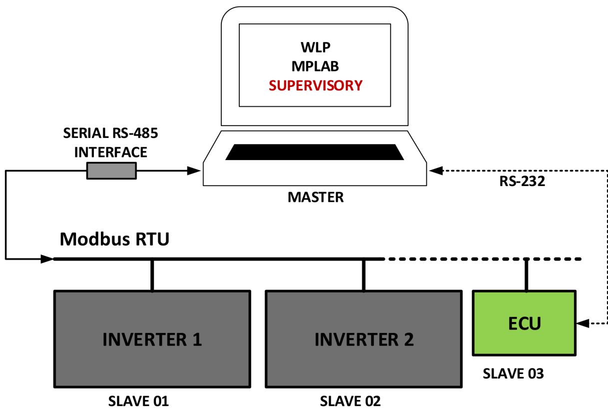

Fig. 6 *Supervisory system of the electric tractor*

voltages, and switching frequencies. Besides, the conception of microcontrollers has also allowed the development of flexible designs, especially when digital signal processors and real-time microcontrollers are employed.

The proposed propulsion system of the electric tractor shown in Fig. 4 employs an ECU, which is responsible for drive management. The ECU also controls the inverters by providing them with the control signals necessary to supply power to the electric motors by the required torque and speed. Sensors are used to measure variables, e.g. position, speed, current, voltage, and temperature. Such signals are properly conditioned before they are sent to the processor. The ECU output signals are sent through interface circuits to the analogue inputs (AI1) of both inverters.

The algorithm associated with the control strategies is executed by the microcontroller. A dsPIC30F4013 by Microchip was employed in the implementation of the ECU [32]. The proposed control concept aims to optimise the performance of the electric tractor during typical manoeuvres associated with the intended application in rural areas. Fig. 5 shows the proposed drive control system. In this design, the commands sent to the inverters are determined based on the speed required by the driver through the

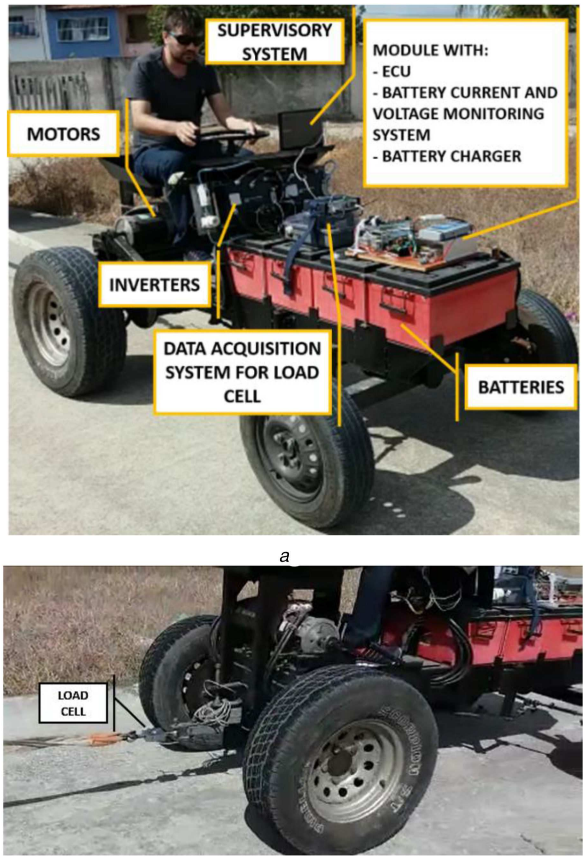

Fig. 7 *Structure of the electric tractor*
(a) Overview, ***(b)*** Load cell coupled to the electric tractor

pedal (V_x), the longitudinal speed (V), the traction wheel speed (V_W), the desired slip ratio according to the soil surface (λ_{ref}), and actual slip ratios measured in each traction wheel (λ_1 and λ_2). Thus, the main resulting functionalities are independent drive control of the inverters, speed control, wheel slip control, and monitoring of the current and voltage of the batteries.

A supervisory system was also implemented to monitor the variables associated with the inverters. By using an integrated data storage function, it is possible to provide performance reports, as Elipse SCADA Software was used for this purpose [33]. The communication between the supervisory system and the inverters occurs through Modbus protocol with remote terminal unit (RTU) transmission mode. Modbus is an open protocol widely used in distinct devices by several manufacturers. Modbus RTU network employs a master–slave system for the exchange of messages. Each communication starts with the master sending a request to a slave, who responds as requested. In both telegrams (question and answer), the structure is the same, consisting of an address, function code, data, and cyclic redundancy check. The master starts the communication by sending a byte to the address associated with the slave. When sending the reply, the slave also initiates the telegram with its address. Fig. 6 shows the proposed structure for the supervisory system, which is employed to monitor the inverters. It is also possible to insert the ECU in Modbus RTU network or access it independently through the communication protocol RS-232.

3 Experimental results

The electric tractor prototype was evaluated to assess its operation and performance properly. The main objective is to analyse the traction characteristic of using with a customised drive system and the proposed control strategy. To enable a proper analysis of the test results with the electric tractor and establish a fair comparison, the methodology followed in the practical drawbar tests has been based on document CODE 2 by international organisation OECD [34], which is applicable to perform tests of agricultural tractors. A conventional tractor using an ICE was also tested for performance benchmarking. The experimental tests are divided into two sections: analysis of the electric tractor in a concrete track and tests carried out in the field.

3.1 Tests in a concrete track

The drawbar force, wheel speed, wheel slip, and tractor speed are the main parameters that define the electric tractor behaviour. Five traction tests were carried out to verify the operation and performance of the electric tractor in a concrete track without enabling the wheel slip control. The supervisory system was used to record and store data from the load cell, inverters, motor encoders, as well as voltage and current sensors of the batteries. Fig. 7*a* shows the electric tractor prototype under test, where the location of the supervisory system, batteries, motors, inverters, and ECU can be seen. The 10 kN load cell shown in Fig. 7*b* was used to measure the traction force on the drawbar of the electric tractor. All tests were developed in a standard concrete track located at the Department of Agricultural Engineering of the Federal University of Ceará, Fortaleza Brazil (geographical data – location/elevation: 3°44′47.7″S 38°34′53.8″W/19 m).

Four traction tests (ETT#1–ETT#4) were performed with the same coupled load. One additional test (ETT#5) was developed at maximum load to evaluate the traction forces and determine the maximum traction limit of the electric tractor. A photograph was taken before the tests can be seen in Fig. 8. Each test was carried out over a distance of 50 m. It is also worth mentioning that (7) is used to calculate the average traction force

$$NF_{tm} = \frac{\sum_{i=1}^{n} F_i}{t_p} \quad (7)$$

where NF_{tm} is the average net traction force (kN); F_i is the measured instantaneous force in the load cell during the time

Fig. 8 *Preparation for the test sessions: the dragged load, in this case, is composed of a two-axle trailer coupled to an ICE tractor model Valtra Series A*

Table 2 Test sheet

Electric tractor prototype ETT#	1	2	3	4	5
test run time (50 m), s	38	38	37.9	37.8	58.4
speed, m/s	1.32	1.32	1.32	1.32	0.86
speed, km/h	4.74	4.74	4.75	4.76	3.08
slip, %	12.28	12.28	13.65	13.42	35.79
drawbar power, W	2573	2467	2429	2336	4082
battery power, W	3998	3880	3795	3685	7145
efficiency, %	64.36	63.58	64.02	63.39	57.13
average drawbar force, N	1956	1875	1841	1766	4768

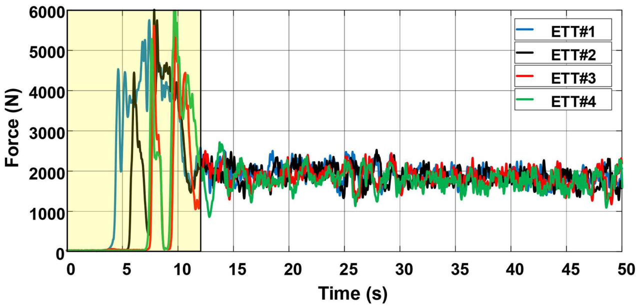

Fig. 9 *Drawbar force during ETT#1–ETT#4*

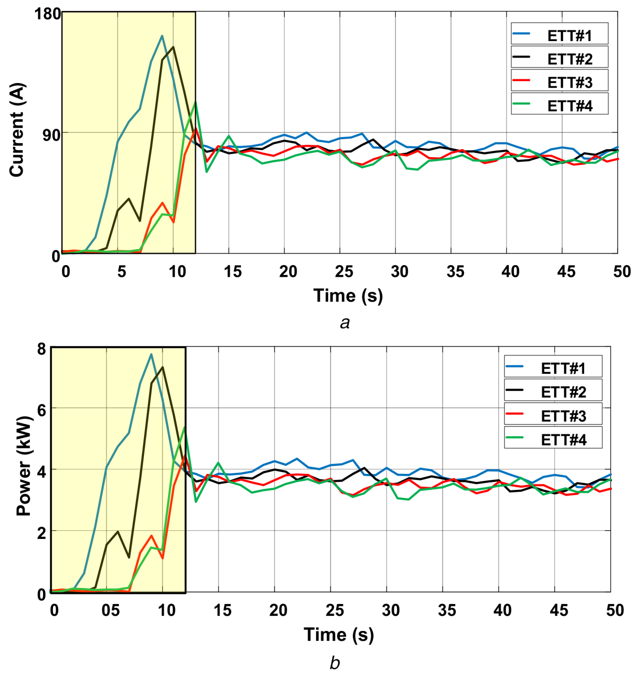

Fig. 10 *Measurements carried out in the battery bank during ETT#1–ETT#4*
(a) Current profile, ***(b)*** Power profile

interval comprising of the actual and last measurements (kN/s); and t_p is the time interval required to travel over the length of the test track (s).

The available drawbar power is a function of the traction force and speed and is calculated as in the following equation:

$$P_d = \frac{F_{tm} V}{3.6} \tag{8}$$

where P_d is the drawbar power (kW); F_{tm} is the average traction force (kN); and V is the speed (km/h).

The efficiency of the electric tractor is determined by the ratio between the output power at the drawbar and the power provided by the batteries according to the equation

$$\eta_{et} = \frac{P_d}{P_b} 100 \tag{9}$$

where η_{et} is the efficiency of the electric tractor (%); P_d is the drawbar power (kW); and P_b is the battery bank power (kW).

By recording data regarding the monitored variables, it is possible to analyse the tractor performance properly. Table 2 presents the obtained results during five electric tractor test sessions (ETT#). Fig. 9 shows the behaviour of the force on the drawbar during the first four tests, i.e. from ETT#1 to ETT#4. From the graphs in Fig. 9 and the data in Table 2, it is possible to observe that the traction forces in the tests remain balanced. In such tests, the electric tractor average speed remains in the range between 4.74 and 4.76 km/h, thus generating an average traction force between 1766 and 1956 N. The average drawbar power varies accordingly between 2336 and 2573 W.

Fig. 10 shows the battery bank performance through current and power graphs in ETT#1–ETT#4. The average battery power varies between 3685 and 3998 W. During test ETT#5 at maximum load condition, the average speed decreased significantly to 3.08 km/h when compared with ETT#1–ETT#4 due to the heavy load. The prototype maintained an average traction force of 4768 N during ETT#5, according to Fig. 11, whereas the average drawbar power was 4082 W. Fig. 12 shows the battery bank performance in ETT #5 through current and power graphs, where the corresponding average battery power was 7145 W.

The energy flow in the system can be represented by the diagram in Fig. 13. The total energy demand from the battery bank given by E_t can be determined from the energy required by the drawbar and losses in the propulsion system according to the following expression:

$$E_t = \int_{t_0}^{t_f} P(t)\,dt \tag{10}$$

where t_0 and t_f are the initial and final time instants associated with the tractor operation and $P(t)$ is the instantaneous power.

The overall system losses are due to the switching losses of the inverters, electromechanical losses of the electric motors, mechanical losses of the transmission system, and friction of the wheels. The overall theoretical efficiency for optimum conditions η_t is calculated based on the individual efficiencies of the tractor

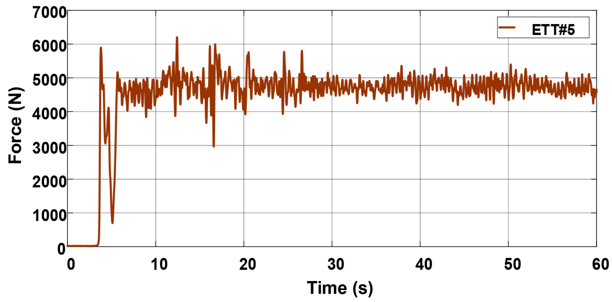

Fig. 11 *Drawbar force during ETT#5*

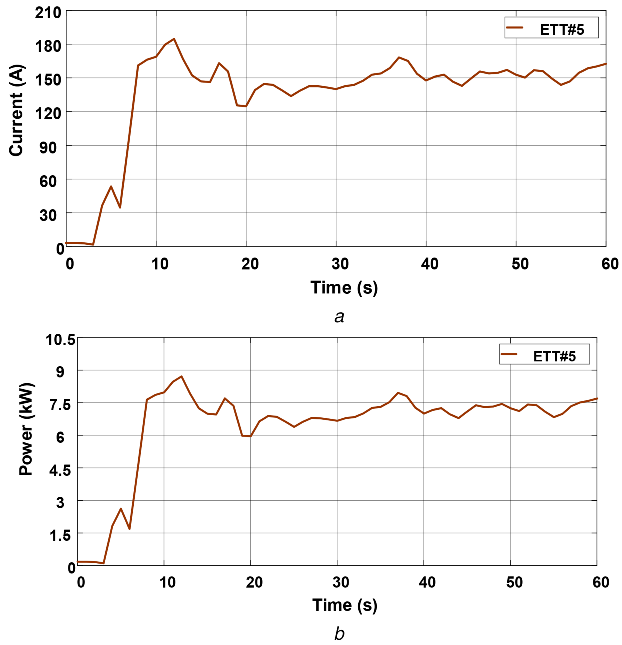

Fig. 12 *Measurements carried out in the battery bank during ETT#5*
(a) Current profile, ***(b)*** Power profile

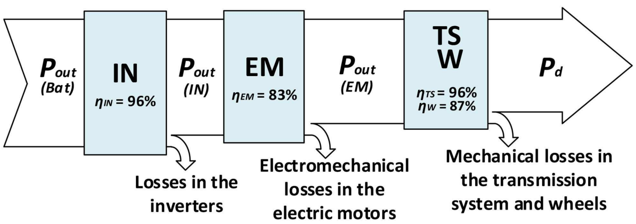

Fig. 13 *Energy flow in the electric tractor*

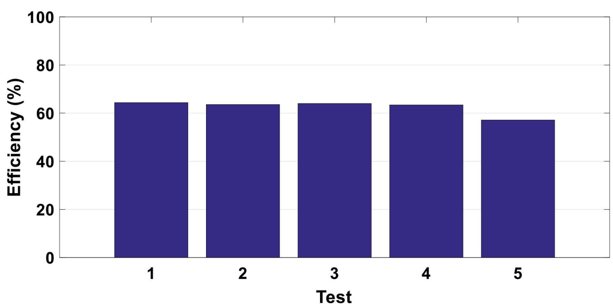

Fig. 14 *Overall efficiency of the electric tractor during the ETTs*

components, as shown in Fig. 13 according to the following expression:

$$\eta_t = \eta_{IN}\eta_{EM}\eta_{TS}\eta_W \qquad (11)$$

where the inverter efficiency is $\eta_{IN} = 96\%$, the motor efficiency is $\eta_{EM} = 83\%$, the transmission system efficiency is $\eta_{TS} = 96\%$, and

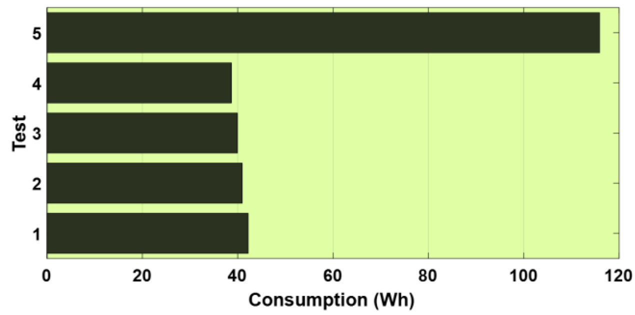

Fig. 15 *Energy provided by the battery bank during the tests*

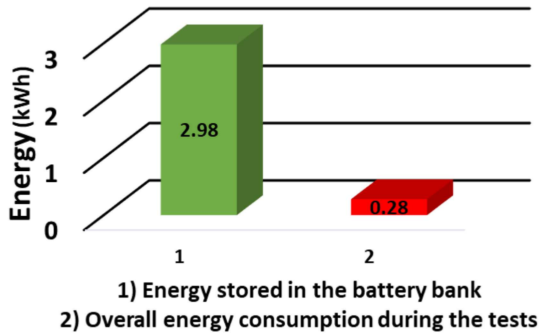

Fig. 16 *Comparison between calculated maximum energy storage capacity and recorded aggregate energy consumption during all test sessions*

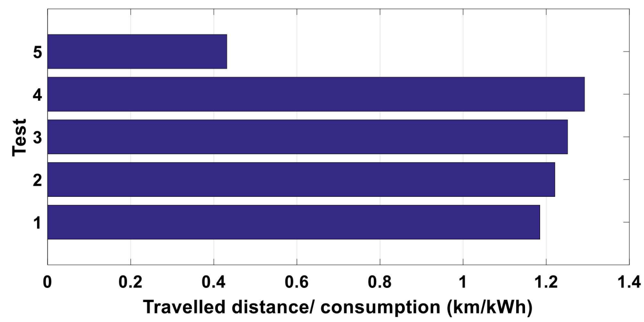

Fig. 17 *Specific range (km/kWh) for each test*

the efficiency between the tyre and concrete surface is $\eta_W = 87\%$ as defined by [35], resulting in $\eta_t = 66.5\%$.

Fig. 14 shows the efficiency obtained for each performed test. The overall efficiency of an electric tractor varies between 63.39 and 64.36% during the first four tests ETT#1–ETT#4. During the test ETT#5 at maximum load, the efficiency was measured as 57%. It can be stated that the values obtained in the tests are very close to the theoretical ones. Besides, the ohmic losses associated with the connection cables were not considered in the calculation, The tyres employed in the experiments are not adequate for tractor applications as well; thus, contributing to increased wheel slip and related losses.

Another important issue lies in energy consumption, which varied between 38.69 and 42.2 Wh from ETT#1 to ETT#4. The maximum consumption of 115.91 Wh occurred during ETT#5 at maximum load. Fig. 15 highlights the energy consumption measured at the battery terminals during each test performed.

A slow charge of the battery bank was carried out before the tests. According to the battery specification, this amounts to the stored energy of 2.98 kWh. On the other hand, the overall energy consumption during the whole test session was 0.28 kWh, according to the graph shown in Fig. 16.

The collected data allows analysing the specific range of the electric tractor in terms of travelled distance per kWh. Fig. 17 shows pieces of evidence that this quantity varied from 0.43 to 1.29 km/kWh during the test sessions.

Fig. 18 *10.3 kW ICE tractor manufactured by Yanmar Agritech*

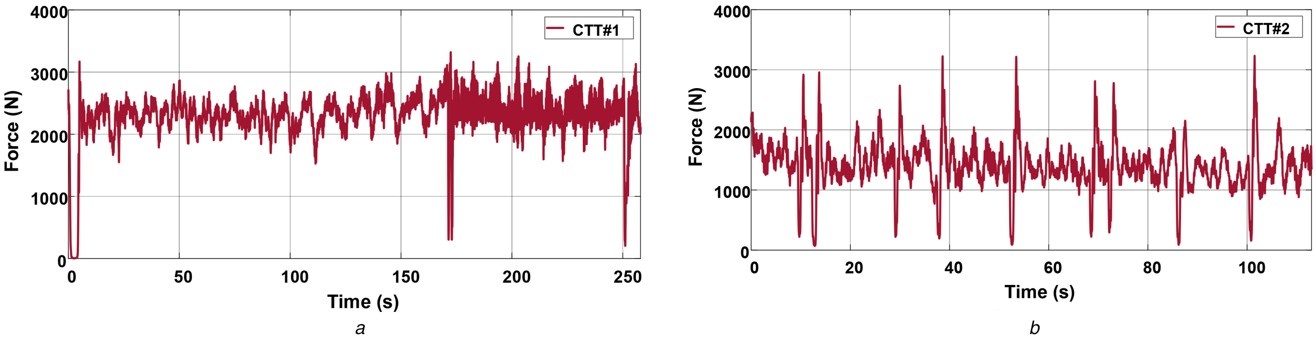

Fig. 19 *Traction force during the tests carried out with the ICE tractor by Yanmar Agritech*
(a) Drawbar force during CTT#1, ***(b)*** Drawbar force during CTT#2

Table 3 Analysis of variance for the comparative tests

Statistic measures	Electric tractor prototype test					ICE tractor test	
	1	2	3	4	5	1	2
sum	3238,482.8	3480,969.4	3139,732.9	2922,937.6	11,471,782.7	26,857,913.1	7998,027.9
samples	1656.0	1856.0	1705.0	1655.0	2406.0	11408.0	5695.0
mean value	1955.6	1875.5	1841.5	1766.1	4768.0	2354.3	1404.4
median	1959.1	1874.9	1832.6	1769.6	4754.7	2365.3	1395.6
minimum	1394.2	1276.7	1232.7	1102.8	2967.7	304.2	69.2
maximum	2587.7	2605.0	2438.3	2374.6	6201.4	3319.1	3231.8
range	1193.5	1328.3	1205.6	1271.8	3233.8	3014.9	3162.6
variance	46,100.4	46,921.6	43,415.2	49,349.9	83,130.5	65,330.5	156,776.3
variance coefficient, %	11.0	11.6	11.3	12.6	7.8	10.9	28.2
mean deviation	214.8	216.7	208.4	222.2	288.4	255.6	396.0
lower quartile	1817.7	1726.4	1698.9	1616.2	4599.7	2220.6	1221.3
upper quartile	2097.5	2018.2	1978.0	1916.8	4924.4	2502.8	1588.7
interquartile range	279.9	291.8	1490.5	300.6	324.7	282.2	367.4

Finally, a conventional ICE tractor was tested for comparison purposes. Two complementary tests (CTT#) were conducted to compare the traction force and other aspects associated with the electric tractor and its more common counterpart. To establish a fair analysis, the two tests with the ICE tractor were performed with the same traction load. A single-axle tractor powered by a 10.3 kW motor manufactured by Yanmar Agritech was selected for this purpose, being represented in Fig. 18. It is worth mentioning that both tractors have nearly the same rated power. In other words, the electric tractor is rated at 9 kW, which is <10.3 kW as provided by the ICE tractor. The same loading was applied to the ICE tractor in this case.

The average traction force of 2365 N was reached in CTT#1 with the first gear engaged at a speed of 0.82 km/h. The average traction force required for the ICE tractor to drag the load was 1404 N at a speed of 1.7 km/h during CTT#2 and with the third gear engaged. The profile of the traction force is shown in Fig. 19. During the two tests with the ICE tractor, the average drawbar power reached 662 and 538 W.

In terms of traction force, Table 3 presents the statistic measures obtained during five tests carried out with the electric tractor, and two tests carried out with the ICE tractor. The following quantities associated with the drawbar force were then determined: the sum of all samples, number of samples, mean value, median, minimum, and maximum, range, variance, variance coefficient, mean deviation, lower quartile, upper quartile, and interquartile range. Analysing Table 3 with respect to the traction force oscillation, a notable difference exists when comparing, for instance, ETT#4 with an average traction force of 1766 N and CTT#2 with an average traction force of 1404 N. In such tests, the samples of the traction measurement for the electric tractor varied from a minimum of 1103 N to a maximum of 2375 N, resulting in a range of 1272 N. For the ICE tractor, the minimum and maximum were 69 and 3232 N, respectively, with a resulting range of 3163 N. This means that the electric tractor was 2.49 times more stable with respect to the traction force oscillation during the tests than the ICE tractor adopted as a reference for comparison purposes. The ICE tractor achieved a constant traction force of 2365 N with a speed of

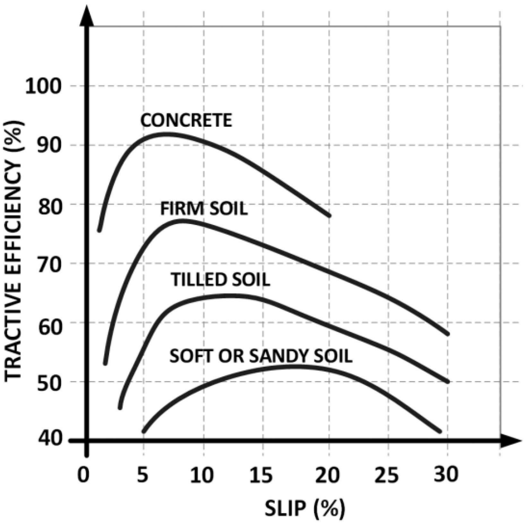

Fig. 20 *Tractive efficiency as a function of slip*

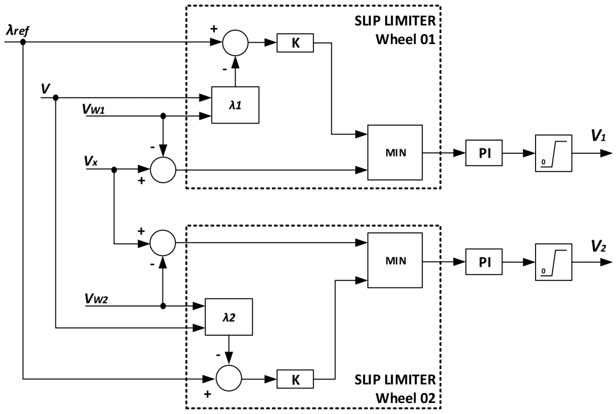

Fig. 21 *Block diagram of the wheel slip control system*

Fig. 22 *Test sessions in a firm soil*

0.82 km/h compared with 4768 N and a speed of 3.08 km/h as achieved by the electric tractor.

The average and maximum noise levels were also recorded during the tests. The maximum noise corresponds to 79 and 84 dB (A) for the electric tractor and the ICE tractor, respectively. In practise, this difference is quite significant in terms of audible noise, since the sound pressure doubles every 6 dB, whereas the sound power doubles every 3 dB.

3.2 Field tests

The electric tractor is a vehicle that presents prominent characteristics for the application of advanced motion control techniques. To maximise its performance, it is essential to associate the forward speed with the attachment of agricultural implement [35]. Part of the energy required by the motor is lost in distinct parts of the system such as mechanical transmissions and auxiliary drives, but most of it is lost during the transmission of energy from the tyres to the ground. Thus, to measure, predict, and evaluate the performance of a tractor, the wheel slip can be considered a key parameter for this purpose while observing certain working conditions found in rural properties. The work described in [36] concluded that different types of soil textures have slipping ranges for which the tractive efficiency would be maximal when the slip of the driving wheels is maintained within the optimum ranges. Fig. 20 shows the relationship between the slip and tractive efficiency for different soil conditions [36].

According to Fig. 20, the slip should be close to the peak value of tractive efficiency for a more efficient operation considering the curve for each type of soil. Thus, the tractive efficiency is maximum when the tractor operates under the following conditions [37]:

- concrete: slip between 4 and 8%;
- firm soil: slip between 8 and 10%;
- tilled soil: slip between 11 and 13%; and
- soft or sandy soil: slip between 14 and 16%.

Thus, it can be stated that the range for the maximum tractive efficiency occurs for a slip between 4 and 16%. To achieve efficient operation of the tractor, there must be some slip between the wheel and the ground, though a limited slip leads to improved tractive efficiency. Wheel slip is required for traction to occur, but if certain limits are exceeded, grip loss and traction reduction may occur. In this context, excessive wheel slip is one of the main factors responsible for degrading efficiency [37]. Wheel slip is directly responsible for reducing the tractor forward speed and consequently has a significant influence on power loss on the drawbar. In agricultural tractors, wheel slip occurs due to a number of factors including the drawbar force required to move certain agricultural equipment, surface type, tyre type and pressure, and wheel load.

Wheel slip should be optimised to ensure good stability and efficiency. Therefore, wheel slip control in the tractor is essential to save energy, increase field capacity, decrease tyre wear, and improve overall efficiency. With the use of an electric propulsion system, it is possible to implement a customised approach capable of minimising such losses. A wheel slip control system is then, in this work, proposed to improve traction capacity and reduce energy consumption during the development of agricultural activities.

For the implementation of the control system, the mathematical model of the system was determined using the identification method through data measured in the electric tractor. Fig. 21 shows the block diagram of the control system used to drive each induction motor. It is possible to note that the ECU is directly responsible for controlling the wheel slip.

To evaluate the performance of the electric tractor in the field, comparative tests were performed with and without slipping control. Three test sessions were carried without wheel slip control (ETT #6–ETT #8), whereas other three test sessions were developed with wheel slip control (ETT #9–ETT #11). The experimental field used for this purpose is located close to the concrete track used in the first experimental stage. The experimental field soil is classified as red–yellow argisol with sandy-loam texture. Therefore, it can be considered a firm soil with cone index around 1500 kPa, which represents the soil strength given by the average force per unit area required to force a vertical cone-shaped device into the soil at a constant rate as described in [38]. Each test was performed in a field area whose length is 15 m. The load dragged by the electric tractor, in this case, is composed of an agricultural sprayer coupled to a 10.3 kW ICE tractor. A photograph taken during the field tests can be seen in Fig. 22.

In the experimental field tests, the maximum speed of the induction motors was adjusted to 800 rpm, which ensures an average speed of 3.24 km/h on the traction wheels. During tests ETT #9–ETT #11, the slip reference was set at 10%, which is appropriate to this soil type. The obtained results can be observed Figs. 23 and 24.

From the graphs, it is possible to note that the electric tractor presents a considerable improvement in terms of stability and energy consumption when the wheel slip control is adopted. During tests ETT #6–ETT #8, the electric tractor achieved an average speed of 1.8 km/h with an average slip of 41.5%. On the

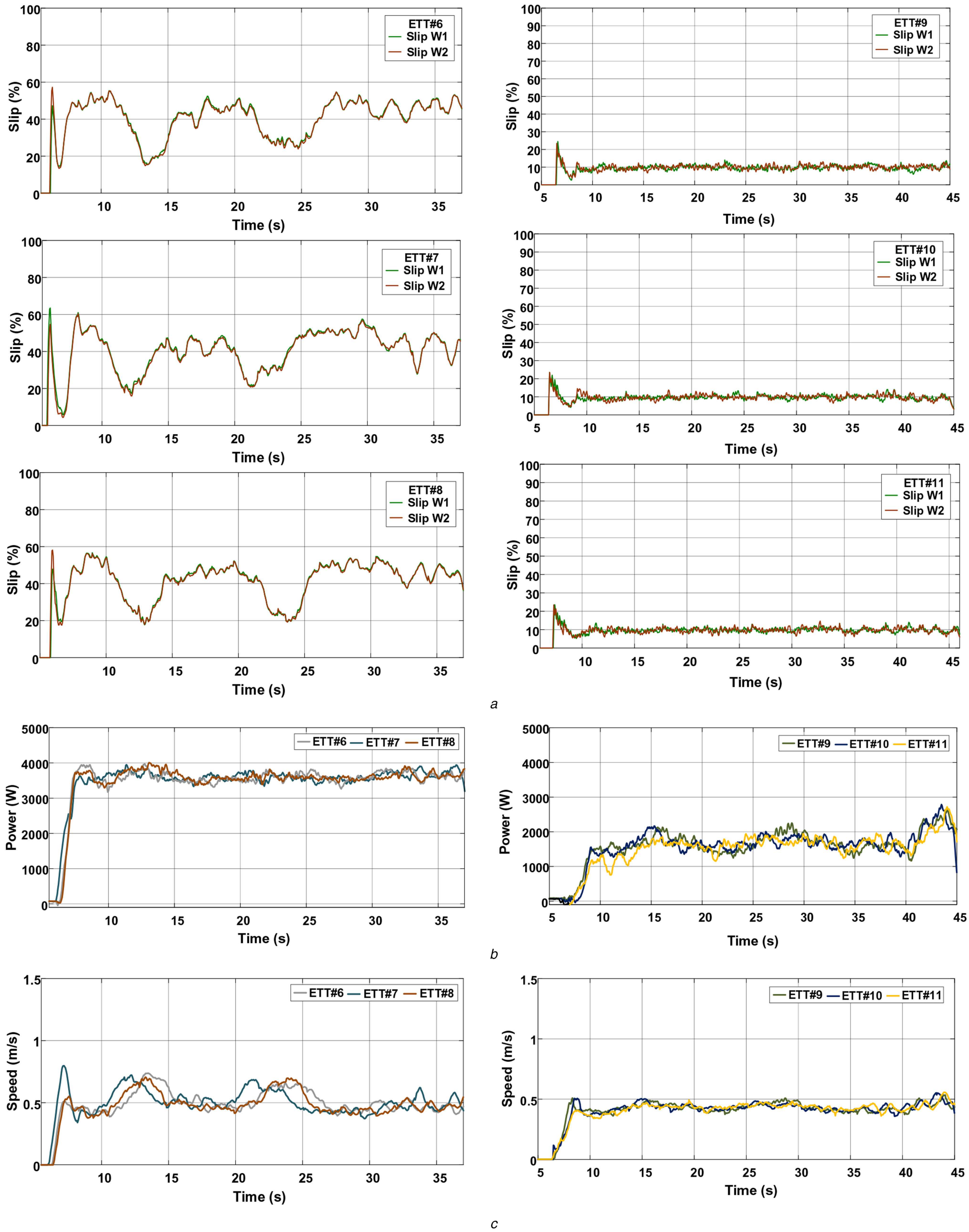

Fig. 23 *Experimental field results obtained with electric without and with wheel slip control*
(a) Wheel slip, ***(b)*** Power extracted from the battery bank, ***(c)*** Speed

other hand, the average speed is 1.545 km/h with an average slip of 9.77% during tests ETT #9–ETT #11. Despite there is a small reduction in speed, the adopted control provides greater stability to the electric tractor with a more uniform speed. The energy consumption is reduced from 29.92 to 16.24 Wh when the wheel slip control is adopted, representing a saving of 46%. This aspect is also clearly evidenced in the profiles represented in Fig. 24. Table 4 summarises the results obtained during six test sessions of the electric tractor in an experimental field.

3.3 Cost estimate and comparison of the proposed electric tractor with an ICE tractor

A cost analysis is presented as follows based on the Brazilian market prices for locally available products in 2017. The cost of

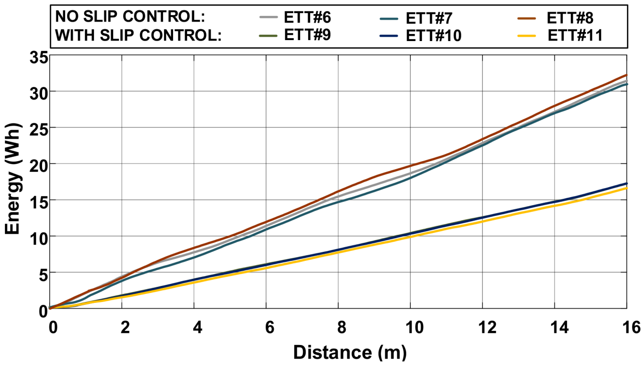

Fig. 24 *Analysis of energy consumption when the electric tractor operates with and without wheel slip control*

Table 4 Results obtained during the field tests

Electric tractor prototype						
ETT#	6	7	8	9	10	11
test run time (15 m), s	30	29.4	30.1	34.88	34.8	35.12
speed, m/s	0.5	0.51	0.498	0.43	0.431	0.428
speed, km/h	1.8	1.836	1.792	1.548	1.551	1.537
slip, %	41.5	41.46	41.54	9.8	9.76	9.76
battery power, W	3596	3612	3621	1695	1709	1618
energy, Wh	30	29.49	30.27	16.42	16.52	15.78

Table 5 Initial cost associated with the electric and ICE tractors

Electric Tractor	Batteries	PV system	Total
€10,746	€5801	€8262	€24,809

ICE Tractor	Diesel storage tank	Total
€5964	€535	€6481

Table 6 Comparison between the electric and ICE tractors

Total hourly operating costs, €/h			
Utilisation, h/year	Maximum daily working hours	Electric tractor hourly cost, €	ICE tractor hourly cost, €
Neglecting energy surplus			
250	6	6.43	5.23
500	6	3.66	4.06
Considering energy surplus at 0.03 €/kWh			
250	6	5.22	5.23
500	6	2.44	4.06

imported equipment is calculated considering the exchange rate valid for 4th September 2017 of €1.00 = R$3.70 or US$1.00 = R3.10. To calculate the depreciation of the equipment cost, the following periods are considered: 12 years for the tractor and 25 years for the photovoltaic (PV) modules. Yearly insurance costs are included with 1.5% for the initial investment and maintenance costs of 0.5%/100 operating hours of the tractor. Interest rates are not taken into account. Battery costs are included in the calculation process in terms of operational costs since the degradation occurs in proportion to the number of charging cycles and depth of discharge. Li-ion batteries are used in the electric tractor based on an expected future cost of US$120.00/kWh associated with the storage capacity from 2020 onwards.

Determining the generation and storage capacity of the electrical system takes into account the efficiency of all required components. The maximum daily energy consumption is obtained considering a maximum of 6 h in an alternative working regime at 80% of the tractor rated power. The calculation of the capacity regarding the battery bank and PV generator is based on the power required by the induction motors. Besides, the component efficiencies are also adopted in the estimation.

It can be stated that the initial cost of the electric tractor system is €24,809 according to Table 5, which is up to four times higher than that of the ICE tractor, i.e. €6481. However, it is worth mentioning that such a high cost is also due to the energy conversion system based on PV solar energy.

For average solar radiation of 5 kWh/(m^2 day) typically available in equatorial regions, the amount of energy generated by the PV system would not only be enough to supply the electric tractor adequately, but also to inject the surplus in the utility grid. In this case, the payback time can be significantly reduced, considering the cost reduction of the electricity bill. Besides, the generated energy can be used for distinct tasks in the context of family farming, e.g. water pumping, lighting, heating, and among others. This aspect is evidenced in Table 6, where the cost of the energy generated by the PV system is estimated at €0.03/kWh.

4 Conclusion

This work has presented an updated review on the application of electric tractors, while also proposing an electric propulsion system for small-sized equipment dedicated to family farming applications. The goal is to validate the feasibility of operation and performance of an electric tractor experimentally. It becomes evident that research regarding propulsion systems applied to electric tractors and the respective performance analysis is not yet well-consolidated and discussed in the literature compared with the state-of-the-art of urban EVs.

An electric propulsion system for low-power electric tractors has been designed, implemented, and thoroughly evaluated. By using two inverter-driven induction motors and the ECU, it was possible to demonstrate and evaluate the controllability and traction characteristics of the electric tractor. Besides, a supervisory system was successfully developed using Elipse SCADA. This approach provides the monitoring of distinct variables associated with the electric tractor operation, which is essential for performance evaluation. Simultaneously, data could be stored for an in-depth analysis. Experimental tests were performed to evaluate the operation of the propulsion system, which comprise of electric motors, inverters, and the ECU. The experimental results have demonstrated the viability and effectiveness.

Experimental results have also been obtained from two distinct test sessions that are presented. In the first one, traction tests were performed with the electric tractor in a concrete track, while the results were compared with those obtained with an ICE tractor. It can be stated that the proposed approach is able to achieve superior performance in terms of the steadiness regarding the traction force and speed at significantly lower noise levels. Even though the electric motor's power (9 kW) is less than the combustion diesel engine power (10.3 kW), the recorded traction force of the electric tractor of 4768 N exceeds substantially the traction force of 2365 N developed by the ICE tractor.

In the second stage, comparative tests aiming at investigation evaluate the performance of the electric tractor in the field were presented with and without slipping control. Despite there is a small reduction in speed, the adopted control strategy provides greater stability to the prototype with a more uniform speed. The energy consumption is reduced from 29.92 to 16.24 Wh when the wheel slip control is adopted, representing a saving of 46%.

A cost estimation analysis has also been briefly discussed; thus, denoting that the electric tractor application is quite prominent in a more complex scenario involving distinct primary energy sources. Considering this aspect, it is possible to promote more sustainable development in family agriculture with the introduction of such equipment as an agriculture tool, especially because it can be supplied by clean and renewable energy sources such as the one proposed in this work. In semi-arid regions, for example, PV solar energy can be used. In other regions and agricultural societies, other renewable energy sources such as wind and biogas can also be considered as possible choices.

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