STUDY ON THE BEHAVIOR OF A BATTERY MOUNTED ON AN ELECTRIC TRACTOR PROTOTYPE
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STUDIU PRIVIND COMPORTAMENTUL UNEI BATERII DE ACUMULATORI MONTATĂ PE UN PROTOTIP DE TRACTOR ELECTRIC

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ABSTRACT
In this article it is studied the behaviour of a rechargeable battery, which outputs a maximum power capacity of 17 kWh that's being used as the main source of the prototype electric tractor developed at INMA Bucharest. This tractor is equipped with 16 kW electric motor, 4 speed gearbox and 4x4 traction. The charging mode of the battery when it is supplied with different powers from the current source was studied, but also the power delivery mode when the tractor is in operation and different loads occur. The energy consumption of the battery has also been studied, from the moment when the tractor is put into operation, driving on flat asphalt or agricultural land, with or without load and also in extreme traction conditions, for ploughing or towing heavy loads.

REZUMAT
În acest articol este studiat modul de comportare a unei baterii de acumulatori, care poate debita o energie maximă de 17kWh, ce este folosită ca sursă principală de energie la prototipul tractorului electric dezvoltat în cadrul INMA Bucuresti. Tractorul este echipat cu un motor electric cu putere 16kW, cutie de viteze cu 4 trepte și tracțiune 4x4. A fost studiat modul de încărcare al bateriei atunci cand este alimentată cu puteri diferite de la sursa de curent dar și modul de livrare a energiei atunci când tractorul este supus diferitelor regimuri de lucru în functionare. De asemenea a fost studiat consumul de energie din baterie de la momentul cand tractorul este pus în funcțiune, rularea pe teren plan, asfaltat sau teren agricol, cu sau fără sarcină dar și în condiții extreme de tracțiune, la lucrări de arat sau tractarea unor sarcini mari.

INTRODUCTION
Romania's agricultural area is about 14 million ha, ranking 7th place in Europe, 9.7 million ha of which are arable land.

The processing in the modern agrotechnical conditions targeting at this surface, implies a complex technical-material base, in which the agricultural tractors have the main role. (*Ministry of Agriculture and Rural Development*).

According to the population density of Romania, each inhabitant has about 0.41 ha of arable land, a value superior to many countries in the European Union and almost double the EU average, which is 0.212 ha/inhabitant.

On a farm in Romania, a tractor is used for about 10,000 hours after which it is taken out of use, while in other U.E. member countries, the use of a tractor on a farm does not exceed 4,000 hours (*www.madr.ro*). According to statistics (figure 1), until 2016, over 200,000 tractors were officially registered in Romania. Analysing this data, it can be seen that from 1990 to 2016 the number of tractors increased by about 50,000 units. We can consider that of the 150,000 tractors registered before 1990, a large part was in operation in 2016 as well. These units certainly do not meet the new environmental protection requirements and the pollution of the environment by them is significant.

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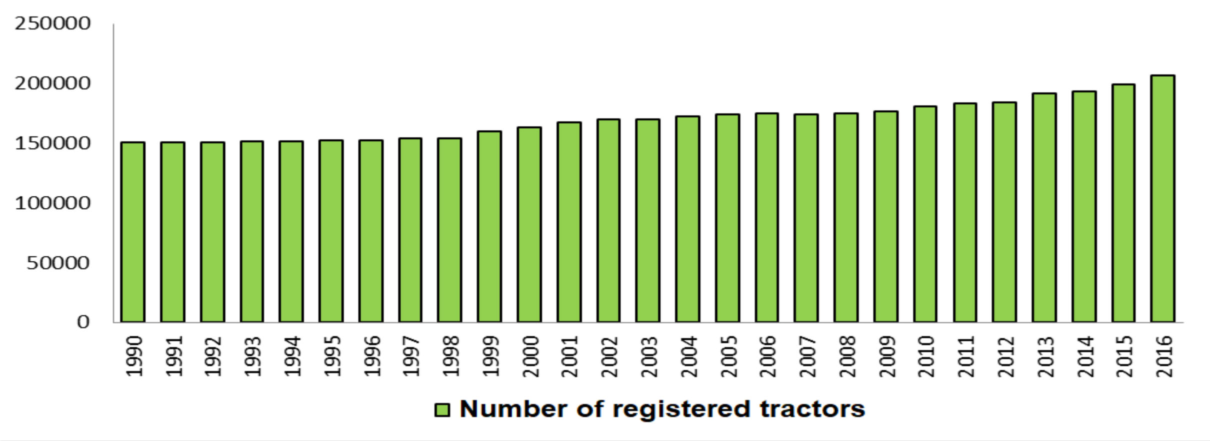

Fig. 1 - Evolution of the number of tractors in Romania

It has been shown that noxious substances lead to acid rain, ozone depletion and soil degradation. Monoxide and nitrogen dioxide (NOx) are gases generated as a result of combustion, when the engine is hot, and material particles (PM) which are composed mainly of carbon particles and other substances harmful to the environment and life, occur as a result of incomplete combustion of fuel during the operation of heat engines, especially when the engine is colder.

Specific regulations have been created to reduce the emissions generated by heat engines and the new conditions imposed by Tier 4 on reducing pollution have led to changes in the construction of tractor engines and combine harvesters. The regulations imposed by Tier 4A came into force on January 1, 2011, setting the levels of particles and pollutants allowed for heat engines over 174 hp (130 kW), and the emergence of Tier 4B regulations led to the need to meet more drastic conditions, with applicability from 2014, for all heat engines that fall under the scope of these regulations (*https://www.agrimedia.ro/articole/scr-devine-o-certitudine-la-tractoare-si-combine*).

These regulations are studied and amended so that pollution is reduced as much as possible, thus creating new documents in the field, such as: Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC to improve and extend the Community scheme for greenhouse gas emission allowance trading (EU emission allowances, "EU ETS") and Decision 406/2009 / EC of the European Parliament and of the Council of 23 April 2009 on the efforts of Member States to reduce greenhouse gas emissions so as to comply with the Community's commitments to reduce greenhouse gas emissions by 2020 (Decision on the sharing of efforts, "ESD"). There are studies conducted worldwide that show very clearly that the use of renewable energy reduces oil consumption and as a result, emissions are reduced. In support of these studies, vehicles have been designed and built that are powered by renewable energy and that are clean from the point of view of pollution. Well-known manufacturers in the field such as John Deere, Solectrac, Fendt and others already have in their portfolio prototypes of electric tractors. *Huisong Gao* presents the main concerns that exist even at the level of small manufacturers for the development of electric tractors (*Gao H. et al, 2020*). There are concerns about lowering the price of electric tractors by replacing expensive electronic control components with other equipment that performs the same tasks but is much cheaper and can be programmed using existing programs in research laboratories. *Yanni Chen* and colleagues demonstrate how to replace the controller of an electric tractor, an expensive component of the propulsion system, with a programmable logic circuit that is much cheaper (*Yanni Chen, et al, 2016*). Energy savings are highlighted in the study conducted by *Oscar Lagnelöv* which compares the charging systems used in electric tractors (*Lagnelöv O. et al, 2020*).

In densely populated countries, such as India, the problems posed by pollution and fuel economy are widely studied and the introduction of new technologies in agriculture occupies an important place in research (*Ashish M., et al, 2020*).

Some of the advantages of clean energy sources (green energy) compared to conventional energy sources (fossil energy sources or energy sources that are depleted and there is no possibility to regenerate), could be the following:

1. extremely low pollution and environmental impact;
2. they can ensure energy independence;

3. they can provide energy to activities carried out in territories where there is no possibility of connection to the electricity grid;
4. new branches of industry can be developed;
5. they are sources of income;
6. they are easily renewable.

Often, the use of renewable energy sources requires a higher financial effort, incurring additional costs with the distribution and recovery of this type of energy. As a result, such projects involve financial solutions to reduce payback periods and increase economic performance.

In this context, this article analyses the behaviour of a rechargeable battery, used as the main energy source for the prototype of the electric tractor developed within INMA Bucharest.

MATERIALS AND METHODS

For the tests, a prototype general purpose electric tractor was used fitted with a 4-speed gearbox for going forward and a shifter to be able to use the 4 gears for reversing (with 4X4 traction), an asynchronous three-phase model AME200 electric motor of 16kW which is controlled by a Curtis controller and a 144V, 120 A rechargeable battery controlled by a management system (battery management system BMS) model Orion 2 (https://www.orionbms.com/products/orion-bms-standard/) used to charge the battery using a 6.6 kW (6.6KW HK-J) charger.

The figure below shows the electric tractor used in the tests.

Fig. 2 - The prototype electric tractor used in the tests

The prototype general purpose electric tractor has been designed to be used with electric motors with powers from 6kW to 50kW, has 4X4 traction, hydraulic system for both power steering and agricultural equipment that can be connected to the tractor and a PTO with 2 speeds (540 and 1000 rpm). Given that this tractor is designed to use only the electrical power generated by a battery, all electronic subsystems are designed for low power consumption. The main technical characteristics of the electric tractor are:

- Maximum length: 3330 mm;
- Maximum width: 1530 mm (with mirrors 1730 mm);
- Maximum height (cabin): 2530 mm;
- Wheelbase: 2020 mm;
- Gauge: 1280 mm front; 1250 mm rear;
- Ground clearance: 260 mm (front);
- Total weight: 1970 kg;
- Maximum speed from GPS: 28 km/h.

The battery used is built from 10 3.6V cells mounted in series; there are 4 such packages that are all connected in series. At the cell level there is a temperature sensor used by the BMS to accurately monitor the "health" status of each cell. Also, with the help of specialized sensors, the BMS has information on the state of charge of each cell.

The figure below shows the construction of the battery.

Fig. 3 - 144V battery

When charging the battery, a 6.6 kW charger is used which, with the help of a control network (Controller Area Network, CAN Bus), communicates with the BMS and the motor controller to determine the charging mode according to the existing power of the mains. Battery parameters are saved and archived on an SD card, and can be viewed with a computer using specialized software

The connection block diagram is shown below (figure 4) (*cdn.shopify.com/ s/files/1/1820/0269/files/ orionbms 2_wiring_ and_ installation_ manual.pdf ?12896325426840488 31*).

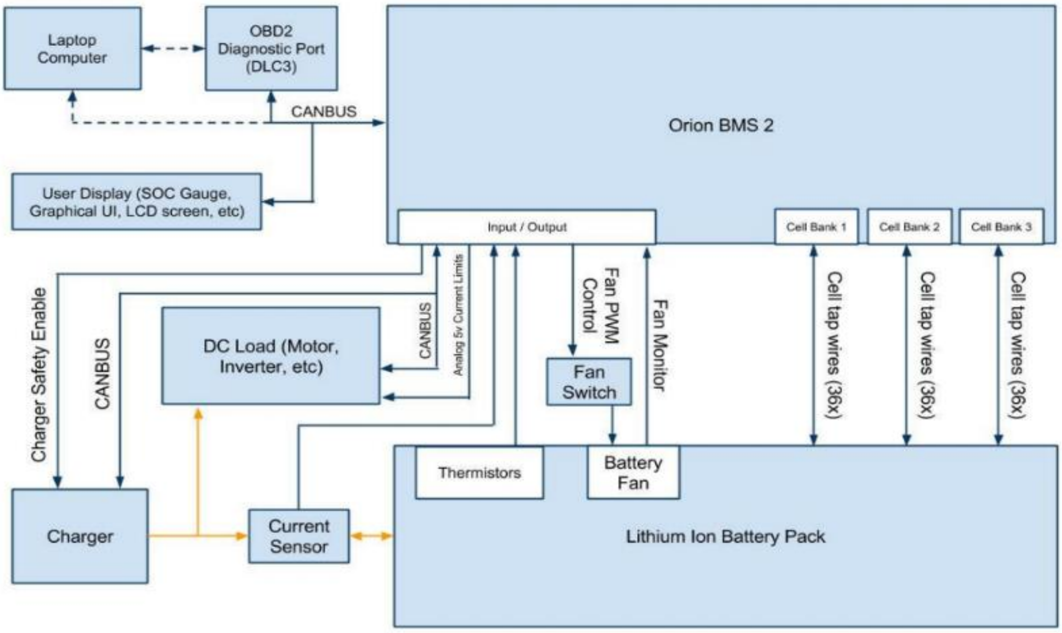

Fig.4 - System connections

During the experiments the following parameters were observed:

1. The time required to charge the battery;
2. Operating time of the battery on the tractor without load, on level ground;
3. Operating time of the battery on the tractor, having different loads and on rough terrain;
4. Maximum traction force on asphalt, until loss of traction;
5. Maximum traction force in the field, until loss of traction.

Prior to the start of the test, the battery was subjected to a series of three charge-discharge cycles on the test bench for the batteries, in this way the cells that make up the battery are brought into a normal mode of operation, thus avoiding the possibility of occurrence during the tests of errors that could alter the final results. The charger used has a maximum power of 6.6 kW, is designed to charge LiFePO4/lithium cell-based batteries and is thus designed to communicate with the battery management system. It is a charger that has a high efficiency, high stability, small size and high degree of protection (IP67). It also has an energy efficiency of up to 95% and only 93% at maximum power, operating over a wide range of input voltages AC90V ~ AC400V 45 ~ 65 Hz, with high tolerance to fluctuations in electrical networks. It has intelligent functions including the possibility of temperature compensation in the charging process, preventing battery damage caused by excessive charging, considerably extending battery life.

The tractor's electric motor controller receives signals from the battery management system, including the battery state of charge (SOC), discharge values, terminal voltage and temperature. According to the information received through the CAN, the monitoring and protection functions are activated for the system, as a whole, to operate safely.

The control system monitors the current, voltage and temperature of the motor and other electrical equipment, which simultaneously send signals to the electronic controller to check the safety of the electrical circuit of the equipment (*Yanni C., 2016*).

Table 1

The main technical characteristics of the charger

Technical data	Value
AC input voltage	AC90 V~AC400 V
AC frequency input	45~65 Hz
AC power factor	≥0.98
Maximum load efficiency	≥93%
IP protection rating	IP67
Operating temperature	-40^{0}C….+55^{0}C
Storage temperature	-40^{0}C…+100^{0}C
Mechanical dimensions (mm)	353(L)*230(W)*160(H)
Net weight	17 kg

Battery parameter visualization software is provided by Ewert Energy Systems, Inc. at https://www.orionbms.com. This software will continue to be used to study the battery.

RESULTS

During the charging tests from a 220 V and 32 A source, an average of 125 minutes required to charge the battery from 10% to 90% of maximum capacity was measured.

The power consumed from the energy source is:

$$P=UI, \text{ (W)} \tag{1}$$

$$P_C=PK, \text{ (W)} \tag{2}$$

where

P- power consumed from the power supply; *U*- power supply voltage, 220V

I- power supply current, maximum 32A; P_C- power charged by the charger

K- loader efficiency coefficient, 0.93%

The graph below shows the voltage of the battery during a 90-minute charge. (figure 5).

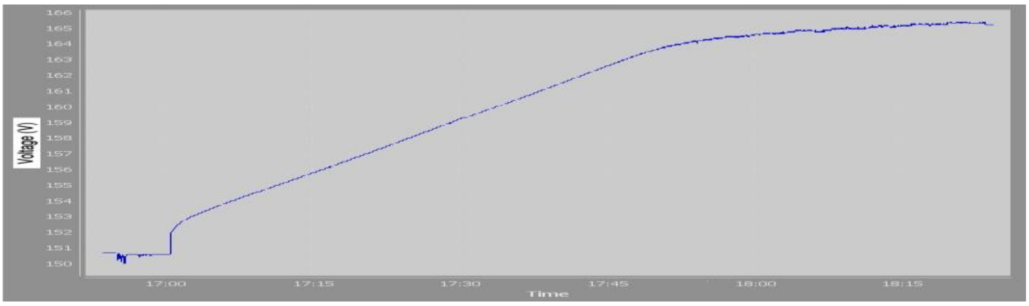

Fig. 5 - Battery charging voltage

Battery charging limits are set by software according to the characteristics of each battery and all these parameters are stored in the internal memory of the BMS. The entire BMS controls the current and voltage values that the charger delivers to the battery.

An example of charging current control is shown in figure 6, for which in settings the maximum charging current was set to 100 A.

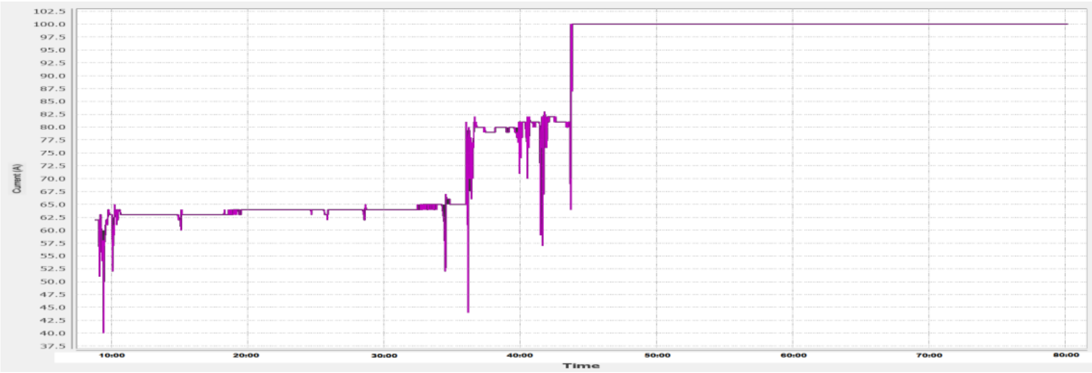

Fig. 6 - Charging current limitation

After charging the battery to 90%, the tractor has been moved on level ground, on asphalt and arable land to establish the autonomy of the battery when the tractor has no other load than that required for self-driving. The maximum speed achieved by the electric tractor prototype was 24 Km/h, the speed indicated by GPS. The tractor operated in these conditions for 260 minutes until the battery reached 10% state of charge. The figures below show the voltage variations that occur at different tractor loads and the voltage drop over time. It can be observed that at the cell level, in percentages, the same voltage variations occur.

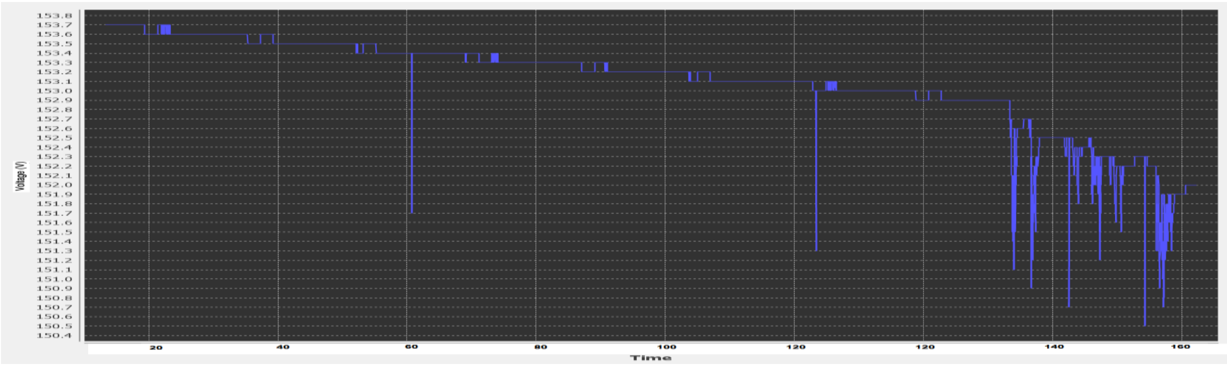

Fig. 7 - Voltage variation during operation for 160 minutes, tractor prototype

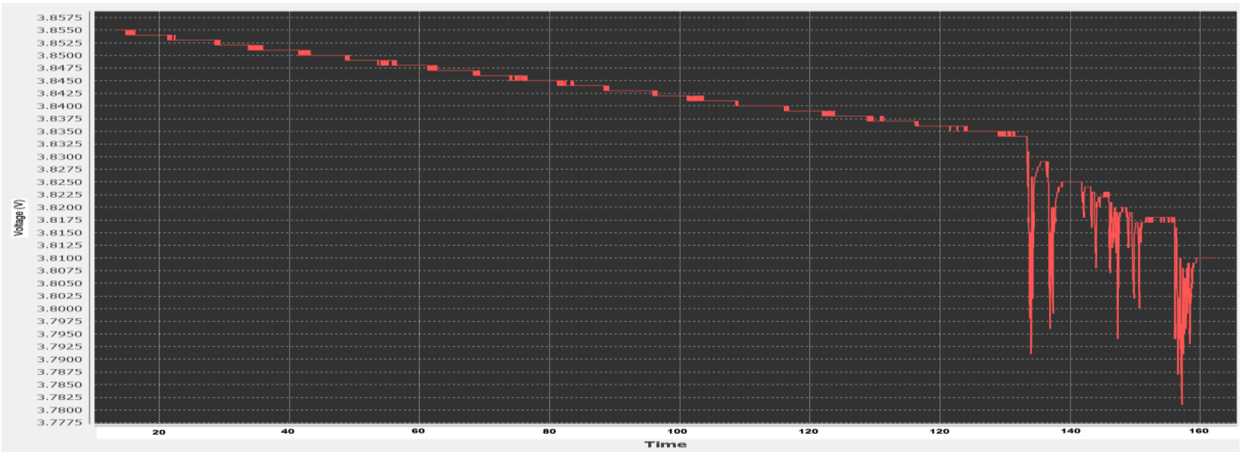

Fig. 8 - Variation of voltage at cell level during operation for 160 minutes

During the next charge of the battery, up to 90% of capacity, a power source of 220V and 16A was used, resulting in a charging time of 254 minutes.

The load test was performed with an empty trailer, weighing 1800 kg, to which were added standard weights totalling 2000 kg. The route was made on flat land (asphalt and agricultural land), rough terrain and arable land. The tractor operated in these conditions for 217 minutes.

In figure 9 a decrease in voltage can be seen, when the tractor has a load for 60 minutes, it goes from 164.8V to 161.2V with peak voltage drops of up to 159.8V.

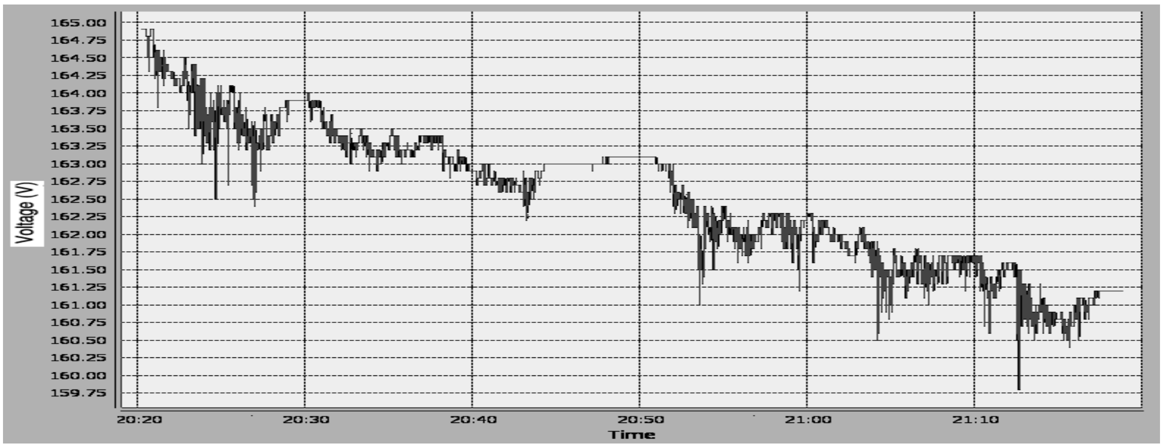

Fig. 9 - Voltage variation in one hour of operation with load

Current consumption under the same conditions can reach peaks of up to 61A, this is highlighted in figure 10.

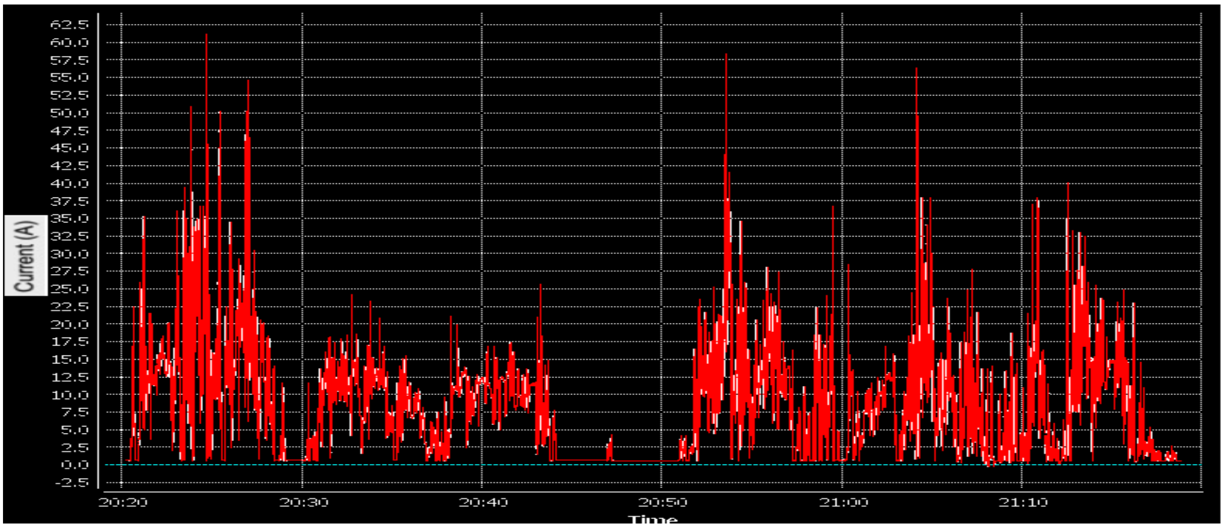

Fig. 10 - Current variation in one hour of operation with load

Another charging test was performed using a 6Ah power outlet. Using this power source, the battery had to be charged for 11 hours to reach 90% state of charge. The graph below shows 5 hours of charging.

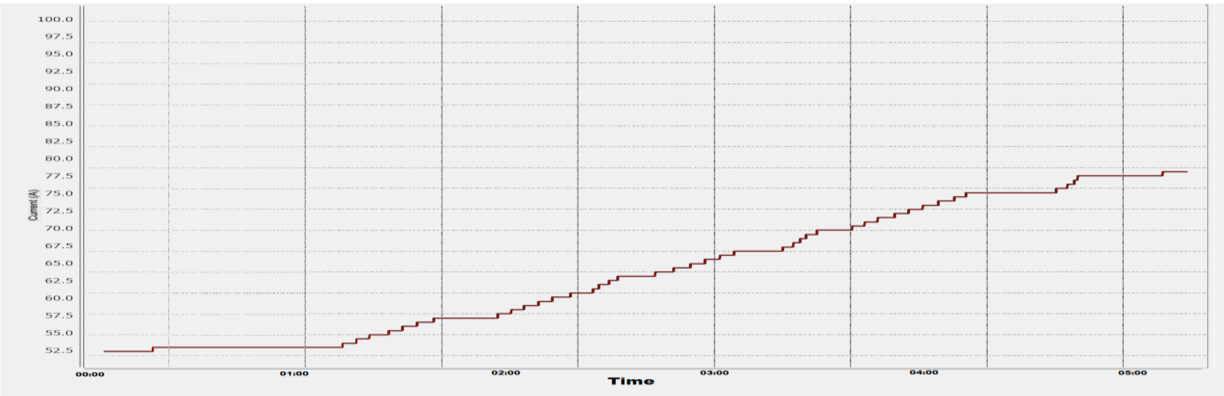

Fig.11 - Amperage graph during 5 hours of charging

The figure below shows the voltage increase graph when charging from a 6Ah source:

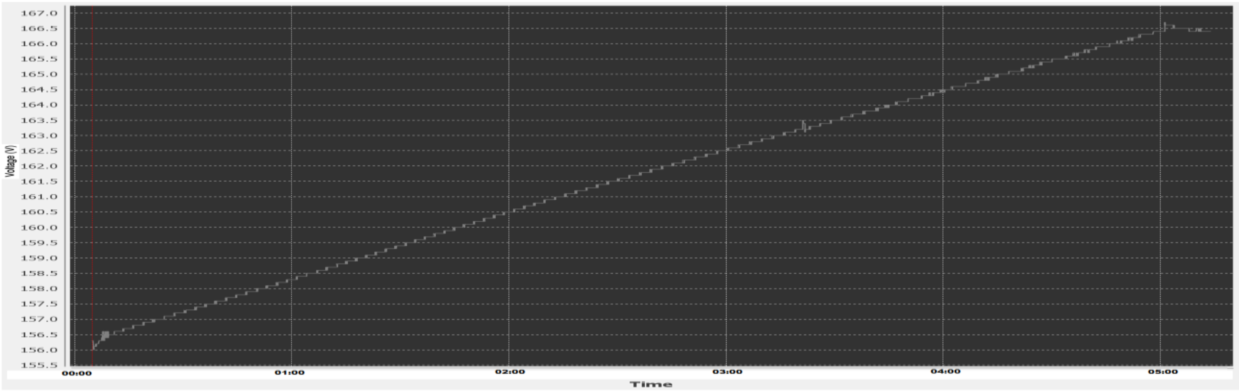

Fig. 12 - Voltage graph during 5 hours of charging.

After the battery was charged to 90% capacity, the tractor was used for one of the heaviest tasks that can be assigned to a tractor, namely the basic tillage (ploughing), for about an hour. The surface shown was 2000 sqm, the working depth of the reversible plough with two furrows being 20 cm.

During this task, the battery power consumption was monitored. The current consumption is shown in figure 13; the current peaks that occur at high loads, reaching over 400A, can be clearly seen.

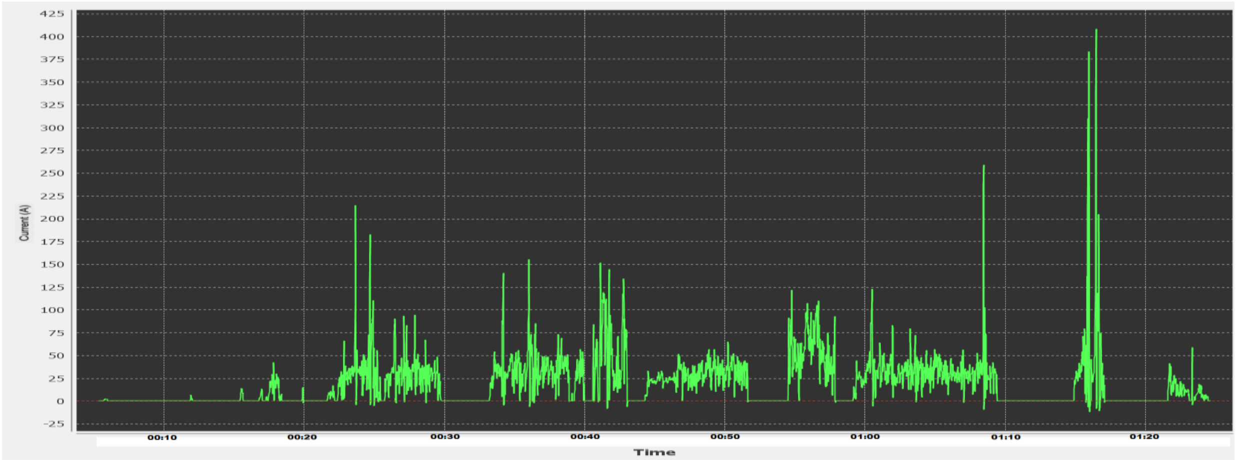

Fig. 13 - Ploughing current consumption

In addition to the current, we also have the voltage variation that occurs for the load conditions to which the tractor is subjected, figure 14 showing the voltage drop while the tractor was ploughing. Under these conditions, the voltage drop in 80 minutes is 8.6V, from 157.8 to 149.2V with a peak drop of up to 138.2V.

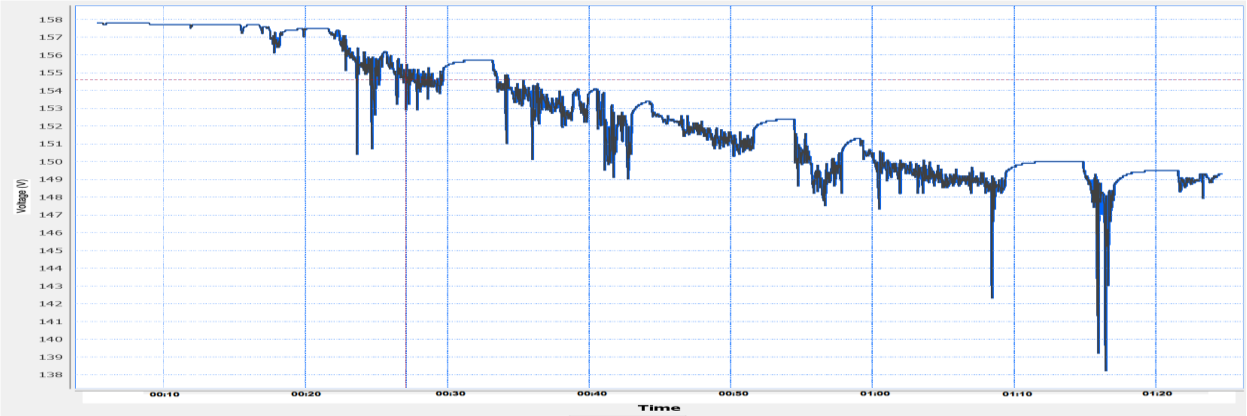

Fig. 14 - Voltage drop during ploughing

Globally, research in the field of tractor construction is aimed at optimizing fuel consumption, reducing maintenance costs, increasing the interval between overhauls and thus increasing the number of operating hours of tractors. Research into the construction of tractors aims not only to increase economic efficiency but also to drastically reduce the pollution generated by the production of a tractor but also the pollution produced by a tractor over the entire period from the sale of the tractor to decommissioning.

Thus, in order to assess the actual power of a tractor, tests are carried out by means of the drawbar under controllable and well-established conditions. Force measurement may also be performed with dynamometric vehicles (DV) which are vehicles specially instrumented and designed to measure the horizontal force on the traction of agricultural tractors. The CREA laboratory in Treviglio, Italy, has designed a new torque tester for tractors with up to 200 kW (245 kW at the wheel) and a maximum traction force of 118 kN (12032.65 kgf) (*Cutini M. and Bisaglia C., 2016*).

The traction test was performed on asphalt, the traction tires used were size 11.2-24 on the rear axle and 6.00-16 on the front axle. As the front axle load is low for this type of tractor, the use of wheels with a diameter equal to that of the rear wheel is not justified (*Duțu M.F., at al, 2019*). The traction test was performed on agricultural land in the same atmospheric conditions, the temperature in the atmosphere being 23.1 degrees Celsius and air humidity 45%. The dynamometer used had a measuring range of 50 kN with a division of 0.5 kN.

The tests were carried out by loading the tractor with a fixed load mounted on the ground and coupled to its drawbar. The forces were noted when the slip phenomenon appeared on the drive wheels. The object of the study being the behaviour of the battery, the experimental determinations did not take into account the necessary conditions for the exact determination of all the forces that appear in the tractor-load system.

The following forces resulted from the traction test:

1. Asphalt traction 15 kN (1529 kgf) with 4X2 and 16.5 kN (1682 kgf) with 4X4;
2. Traction on agricultural land 18kN (1835 kgf) with 4X2 and 21.5kN (2192 kgf) with 4X4.

Instantaneous energy consumption when the tractor is subjected to extreme loads, on asphalt with 4X2 traction and maximum slip, is shown in the graph below.

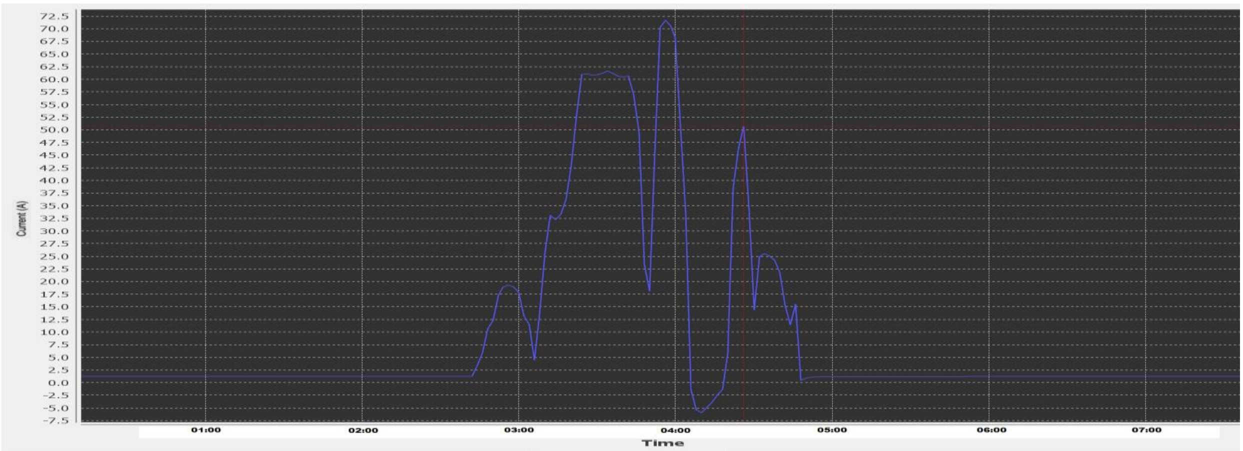

Fig. 15 - Current consumption of the electric tractor prototype at maximum load

The maximum battery current was 71.7 A, the average voltage was 151.5 V resulting in an instantaneous consumption of 10.9 kW. This consumption was recorded at the time of the 4X2 traction test on paved terrain.

CONCLUSIONS

After all the tests performed, it can be considered that a general-purpose tractor chassis can be electrically operated from batteries.

According to the charging / discharging graphs as well as the behaviour in real conditions, it can be said that the battery behaves within normal limits, compared to the results obtained by other electric tractor developers. Charging up to 90% of total capacity took 3 hours, which is the average charging time obtained by other equipment of the same type. The average operating time on duty was approximately 4 hours, being an autonomy that falls within the average reported values in other scientific papers.

The advantages of using the electric tractor, especially indoors, are clearly superior to a traditional tractor. In closed spaces, such as greenhouses or solariums, charging stations with power supplied by the national network or renewable sources can be placed to use the time when the machine is not in use results in an increase of efficiency. If the tractor is used in the open field, there is even the possibility of bringing mobile charging stations that can be located as close as possible to the place where these machines are used, to use solar or wind energy in order to produce the energy needed to charge the batteries.

The best advantage of electrically powered tractors is the lack of emissions into the atmosphere. Another positive aspect is the low impact on the ground because when the machine is powered by a battery there is no risk of fossil fuels leaking that may reach the work surface by mistake or as a result of an accident. The tested battery managed to complete the proposed tasks in conditions very close to normal. Battery manufacturing technologies being in full development will surely end up with a much shorter charging time, extended operating time and a much longer operating time. These things combined with the declining price of batteries will make them a very good replacement for fossil fuels. Also, the replacement of fossil fuels with batteries is already a necessary thing if we look at it from the point of view of pollution. At the moment, the production, integration and use of electricity as fuel may seem financially expensive and inefficient, but the long-term calculation shows that, on the contrary, this technology will bring great financial benefits and especially in terms of environmental impact.

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