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RESEARCH ARTICLE

EFFECTS OF CONSTANT MAGNETIC FIELD ON THE PERFORMANCE AND THE DURABILITY OF LITHIUM LIFEPO$_4$ BATTERIES

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ABSTRACT

In this work, we were interested in improving the performance and durability of LiFePO4 batteries through the application of a constant magnetic field. To do this, we defined three paramanders: kinetic efficiency and coulombic efficiency for the assessment of performance, then internal resistance for the assessment of durability. We also defined three factors: the charging or discharging rate, the magnetic field, and the state of the process. With an experimental device, we tested the IFR 26650 battery according to an appropriate experimental. design. The analysis of the various results obtained shows among that the magnetic field increases the kinetic efficiency, coulombic efficiency and decreases the internal resistance. Thus, the magnetic field improves the performance and durability of LiFePO4 batteries. A search for optimal conditions of battery use shows that, during charging, a charging rate of 0.5 C and a magnetic field of 6 mT must be established and during discharge, a discharge rate of 1 C and a magnetic field of 3 mT should be recommended. These optimal charging conditions procur average 25 % of the increasing of kinetic efficiency, 5 % of increasing of coulumbar efficiency, and 58 % of reducing of internal resistance compared to a 0.5 C charge rate in the absence of a magnetic field. About the optimal discharge conditions, they procurs average 2.6 % of increasing of kinetic efficiency, 8.4 % of increasing of coulomb efficiency, and 26 % of reducing of internal resistance compared to a 1 C discharge rate in the absence of a magnetic field.

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INTRODUCTION

Access to low-cost, optimised, and efficient carbon-free energy is the key to sustainable and harmonious economic development. As humanity's energy needs continue to grow, the challenge of green energy can only be met if scientific progress and technological innovation are mobilized to create new solutions and new designs. It is in this context that several projects developed in recent years are registered. The 2030 agenda of the United Nations (UN) provides through Sustainable Development Goal N°7, to "Ensure access for all to reliable, sustainable and modern energy services at an affordable cost". This imposes the energy mix on a national and international scale. This energy mix requires considering the dual environmental issue and sustainable development (in accordance with Sustainable Development Goal N° 13: "Take urgent action to combat climate change and its impacts"), the development of renewable energy. The variability and intermittency of these renewable energies generally generally leads to the need for their storage. There are several forms of energy storage, including storage in electrochemical form. The electrochemical storage of energy by batteries has now become a major social and economic issue, with enormous progress expected, whetheritis about stationary applications (storage to ensure a balance between production and consumption), embedded applications (tools and portable devices) or traction applications (electric vehicles and hybrid electric vehicles). Among the existing battery technologies, one of the most widespread technologies, nowadays is the technology of lithium-ion. World demand for lithium-ion batteries doubled in 2021, increasing from 162 GWh in 2021 to 340 GWh in 2022(International Energy Agency, 2022). Every second in the world, 1.4 kilogramme of lithium are produced mainly for the manufacture of lithium-ion batteries. At the same time, the manufacturing cost of the batteries rose significantly in early 2022. This increase was facilitated by the Corona Virus pandemic. As a result, one of the chemistries of lithium-ion batteries, LiFePO$_4$ (or LFP) batteries, has become more attractive because it contains neither cobalt nor nickel, and instead uses relatively low-cost and fully recyclable iron and phosphorus.

In Africa, as in several other regions in the world, heavy investments are increasingly being made in the acquisition of these LFP batteries, whose performance inevitably deteriorates due to cyclical and calendar aging. It should be noted in particular: the decrease of kinetic efficiency, the decreased of coulombic efficiency, and the increase in internal resistance of batteries. From then on, scientists competed in ardour and ingenuity to push the limits of these batteries. Thus, a multitude of research works have been conducted and are continuing (Vincent Prodjinonto, 2022)(Jokar A., 2016)(Andrzej Kulka, 2015)(Junming Chen, 2015) (Liu, 2015) (Long, 2015)(Li J., 2015) (Li , 2015)(Chikkannanavar S. B., 2014)(Liu Xu-heng, 2014)(Talebi-Esfandarani, 2014)(Fuwei Mao, 2014)(Huang, 2013)(Jianjun Song, 2013)(Cesario AJPI, 2013)(Chen Y. W., 2012)(Zhang, 2012)(Xu B., 2012) (Fredrick Omenya, 2011)(Xuesong Fang, 2011)(Etacheri , 2011)(Pan M., 2011) (Sun, 2010)(Ge, 2010)(Yung-Da Cho, 2008)(Abbate M., 2005)(Dell R.M., 2001). Most of these works is grouped according to two main lines of research:

- the development of materials used for the composition of the different components of battery LFP and the choice of the most suitable combinations in order to increase performance and durability;
- development a new manufacturing methodology to reduce cost.

Considering all this, it is important to research ingenious and innovative solutions that can increase the performance of $LiFePO_4$ batteries and make them even more sustainable; this for solving the dual socio-economic and environmental problem in accordance with Sustainable Development Goal N°7, 11 and 13.

During their charging phase, batteries involve the process of electrolysis. However, several studies have revealed the effects of the magnetic field on electrolysis. Indeed, the use of the magnetic field in electrochemical systems dates back a long time. This use led to the creation of a branch of physics: magneto-electrochemistry. Previous research has shown that the use of a magnetic field during electrolysis is a way to improve the properties of metallic coatings. The magnetic field induces movement in the electrolyte solution crossed by an electric current. Since 1983, Fahidy has observed an increase of 4 to 20% in the electrical conductivity of electrolysis under a magnetic field (Fahidy, 1983). Earlier in 1982, the work of Olivier showed that the molecular diffusivity of ions is affected by the action of the magnetic field, which becomes a tensor quantity considering axial mobility, transverse mobility and Hall tangential mobility (Olivier, 1982).

Other research show that the magnetic field can modify significantly the transport of matter within the electrolyte. Several studies show that the magnetic field increases with limit currents when applied to the entire electrochemical cell. This increase, up to 200%, is due to a convective flow tangential to the electrode. This flux is generated by the Lorentz force, which decreases the thickness of the diffusion layer. The maximum increase in current is obtained when the magnetic field vector is perpendicular to the current line and parallel to the surface of the electrode. In this conFiguration, there is a critical value of the magnetic field beyond which the rate allowed to have the maximum limit current, is no longer reached. This critical value of the magnetic field is relatively moderate when the electrolyte is moderately concentrated in the active species, and decreases sharply when their concentration increases (Mathon, 2008). Subsequently, Aogaki and al. showed experimentally since 1976, that the Lorentz force can be used to move a fluid (electrolyte). They show that the electrodes/magnetic field device operating as a pump (Aogaki R. , 1976). Later 1984, they explained this fluid displacement by the phenomenon of electromagnetic convection (Fueki, 1984). This idea of using the magnetic field as an electromagnetic pump was confirmed by the work of Aaboubi and al. who show that with the electromagnetic device, the velocity of the flow is directly related to the value of the magnetic field and the flow is created wherever an electric current flows, without generating a transverse movement. However, this system is limited when the concentration of electroactive species is very low, as an intense magnetic field is required to produce an acceptable result (Aaboubi O., 1990). Several studies have focused on the effect of the magnetic field on electrochemical. kinetics. Thus, Kelly shows that when an electrolyte flows between two electrodes, the magnetic field modifies the charge transfer reaction (Kelly, 1977). He explains that, this modification results from the magneto hydrodynamic effect induced by the Lorentz force. This result allowed to develop a device that consists of a rotating an electrochemical cell in the air gap of a magnand. They use this technique to electrodeposit copper in the absence of a generator (Fahidy, 1983). Chou and al. studied the kinetics of nickel deposition on alumina powder in the presence of a magnetic field, in a hypophosphite medium (Chou , 1995). They show that the order of the chemical deposition reaction relative to the hypophosphite species increases with the magnetic field, while the activation energy of the system decreases. After further research, J. Lee and al. showed that the potential and distribution of ions at the interface depend on the strength of the magnetic field. The electromagnetic force that convects the fluid near the interface moves indiscriminately, on the one hand the species created at the electrode and on the other hand the non-active species that have migrated to the interface to ensure locally the electro-neutrality of the solution. As a result, the ionic concentration inside the diffusion layer decreases and becomes close to that of the bath. The conductivity of the solution near the electrode then decreases and the overvoltage increases. The latter, which is insignificant in the case of solutions highly concentrated in carrier electrolyte, becomes important in dilute solution and then disrupts the charge transfer (Lee J., 1997). A. Chiba and al. conclude from the modification of the intensity-potential curves that the cathodic and anodic charge transfer coefficients of the Cu^{2+} / Cu system are modified in the presence of the magnetic field (Chiba A., 1988). The results obtained later in 1990 by Z.H. Gu and al. in the electrodissolution of cooper also show a slight effect of the magnetic field on the slope of the Tafel lines. (Gu Z.H., 1990). On the other hand, J.P. Chopart and al. show by stationary and dynamic electrochemical measurement methodology, that the cathodic and anodic kinetic parameters are not modified in the presence of magnetic field during electrodeposition and electrodissolution of copper in an acidic medium (Chopart J.P., 1991). Faced with all these results, we invested in this work to study the influence that a constant magnetic field would have on the performance and durability of $LiFePO_4$ batteries both in charge and discharge phase.

MATERIALS

$LiFePO_4$ batteries used: In this study, three (03) new battery $LiFePO_4$- IFR26650 were used. One of them is presented in fig. 1 and these technical specifications in table 1

Helmholtz coils: For this work, we sized and made a Helmholtz coil. This consists of two identical circular coils, with the same radius, parallel and placed opposite each other at a distance equal to their radius. We used the Helmholtz coil made to create an almost uniform magnetic field in the center of the device, where a sample of battery $LiFePO_4$ - IFR 26650 is placed for the test. The technical Specifications of the Helmholtz coil made are presented in the following table:

Fig. 1. Batteries $LiFePO_4$ - IFR 26650

Table 1: Technical specifications of the batteries used

Characteristics	Securities
Technology	$LiFePO_4$
Model	IFR 26650
Shape	cylindrical
Nominal voltage	3.2 V
Capacity	3.2 Ah
Stored energy	36864 J (10,24 Wh)
Number of cycles	> 3000 cycles
Operating temperature	-20 to 85°°C
Certificate	CE, UL, RoHS
Dimensions	Diameter: 26mm; Height: 65 mm
Weight	80 g

Table 2. Technical. specifications of the Helmholtz coil made

Characteristics	Values
Radius of each reel	0,125 m
Nature of winding wire	Enamelled copper wire
Class	G 2
Nature of winding wire insulation	Polyestérimide
Number of turns per coil	200
Conductor section (copper without insulation)	0,857 mm²
Wire diameter	100 mm
Maximum current	10 A

Magnetic damping box: As recommended by the International. Commission on Non-Ionizing Radiation Protection (ICNIRP), the limit (or maximum) value for exposure to the magnetic field of any part of the human body is 400 mT. Although this limit value is higher than the maximum magnetic field (6 mT) created during our work, we opted for the realization of a magnetic damping box. The main reasons that led to the realization of this box are:

- future investigations for magnetic fields with higher intensity of magnetic field;
- The limitation of the undesirable effects of electromagnetic induction, direct or indirect, created by the magnetic field produced by the Helmholtz coil on the other parts of the experimental device (battery, ohmic resistor of discharge bench, stabilized power supply, arduino board, current sensor, ...).

We had therefore designed and built a magnetic damping box as shown in the following fig. 2. In this box, we arranged:

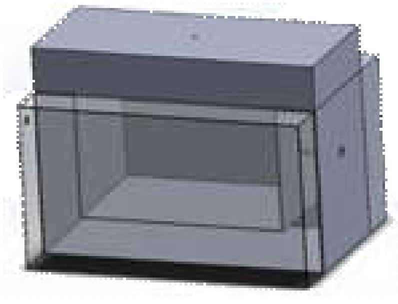


Fig. 2. Magnetic damping box

- The Helmholtz coil that produces the magnetic field
- The $LiFePO_4$ battery to experiment
- Three Hall effect sensors for measuring the strength of the magnetic field produced

Table 2. Main characteristics of the magnetic damping box

Shape	parallelepiped
External dimensions	700 mm x 545 mm x 530mm
External dimensions	480 mm x 319 mm x 310mm
Materials / thickness	Alucobond / 4 mm Glass / 5 mm
Exterior and interior coating	Tar 3 mm

Battery discharge bench: As part of our work, we had made a discharge bench consisting of a band of 05 ohmic resistors KH-216-8_1/10 W. The discharge bench is shown in the following fig. 3:

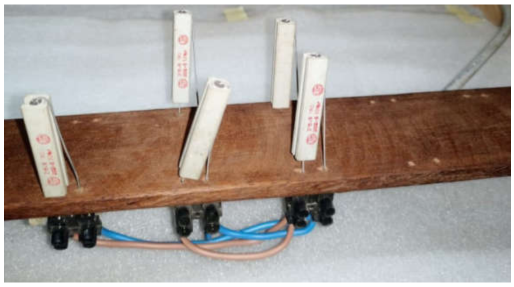


Fig. 3. Battery discharge bench

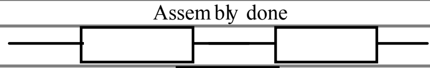
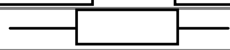
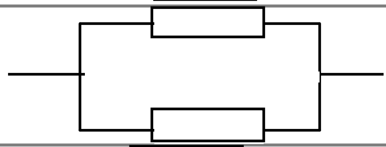
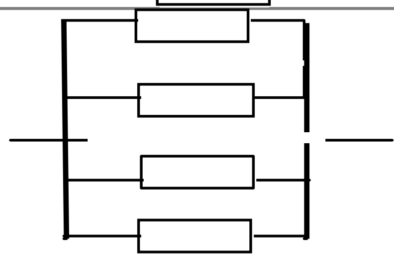
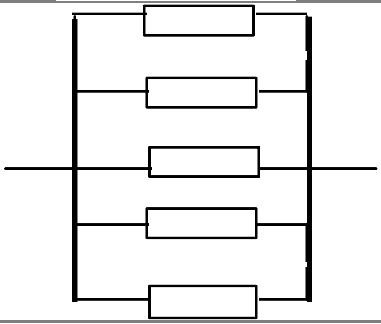
The main characteristics of the ohmic resistor KH-216-8_1/10 W are presented in table 3:

Table 3. Main characteristics of the ohmic resistor KH-216-8_1/10 W

Characteristics	Value
Ohmic value	$1\,\Omega\ \pm 5\%$
Rated power	$10\ W$
Coefficient de température	$\pm 4.10^{-5}\,\Omega\ /K$
Temperature range	$-55°C$ à $350°C$

The mounting of the ohmic resistors on the discharge bench is carried out according to the desired discharge regime for the experimentation of the battery. Table 4 shows the different arrngements made.

Table 4: Assemblies made for the dischargebench

Discharge rate	Assembly done
0.5 C	
1 C	
2 C	
4 C	
5 C	

Data acquisition chain: For the experimentation, we had set up a data acquisition chain composed of:

- three (03) Hall 3305 effect sensors for measuring the strength of the magnetic field at three different locations inside the magnetic damping box: in the center of the Helmholtz coil and on either side of each of the two identical coils;

- one (01) arduino UNO board that collects the information acquired by the installed sensors, processes it and then displays the measured values (magnetic field strength, battery voltage, battery charging, or discharging current intensity, …) on the screen of a computer that records them;
- one (01) SCT 013 current sensor that measures the intensity of the battery charging or discharging current;
- one (01) Mastech MY-60 multimeter that also measures battery voltage;
- one (01) power and harmonic clamp Chauvin Arnoux F27, which measures the instantaneous power delivered from the battery (in the charging phase) or sent into the battery (in the discharge phase);
- one (01) stabilized power GPS-3303 which allows to charge the battery $LiFePO_4$ - IFR 26650;
- one (01) stabilized power supply GPC-3030 which feeds the Helmholtz coil for the creation of the magnetic field.

The entire experimental. device is powered by a 700 VA / 12VDC / 400 Ah caliber Uninterruptible Power Supply (UPS). This UPS makes it possible to avoid disturbances of the experiment, in the event of a power cut or anomaly in the supply of mainly. The experimental device installed excluding the discharge bench, is shown in **Error! Reference source not found.** below:

Fig. 4. Experimental device installed excluding the discharge bench

METHODOLOGY

Development of the DoE (Design of Expermiments): During the experiments, we retained three (03) factors: rate (in ... C) , magnetic field (mT) and state. Factors and levelsused are represented in the following table 5. The answer is kinetic efficiency, coulombic efficiency, and internal resistance. It should be noted that the kinetic efficiency and coulombic efficiency make it possible to assess the performance of the battery, while the internal resistance makes it possible to assess its durability.

Table 5. Factors and levels used for the experiment

Factors	Levels	Number of levels
Rate (in ... C)	0.5 1 2 4 5	05
Magnetic field (mT)	0 3 6	03
State	charge discharge	02

For the construction of the DoE (Design of Experiments), we opted for the complete factorial design. This design includes combinations of all levels of all factors, for a total of 30 experiments. The stabilized power supply GPS-3303 used to charge the battery, given its caliber, does not allow a charging rate beyond 2 C. This reduces the number of feasible experiments to 24. This design of experiments was implemented with the software MINITAB. Each experiment was repeated 03 times with each of the three samples of the battery $LiFePO_4$ - IFR 26650. This ensures the reproducibility of the phenomenon and the repeatability of the results.

Experimental conditions and experimental protocol: Table 6summarises the conditions for experimentation. Experimental protocol followed for taking measurements is described as follows:

For the charging phase

- If the test corresponds to a magneticfieldotherthan 0 mT, adjust the voltage and current at the stabilized power supply GPC - 3030 for the production of the desiredmagneticfield at the Helmholtz coil.
- For the stabilized power supply GPS - 3303, settle the batterycharging voltage to 3.6 V and the maximum chargingcurrentaccording to the charging rate of the test
- Verify the establishment of the data acquisition chain
- If the test is for a magneticfieldotherthan 0 mT, start the stabilized power supply GPC - 3030.
- Turn on the stabilized power supply GPS - 3303 and start recordingmeasurements.
- For the discharge phase
- If it is a test corresponding to a magneticfieldotherthan 0 mT, adjust the voltage and current at the stabilized power supply GPC - 3030 for the production of the desiredmagneticfield at the Helmholtz coil
- Verify the establishment of the data acquisition chain
- If the test is for a magnetic field other than 0 mT, start the stabilized power supply GPC – 3030
- Start recording measurements

Table 6. Experimental conditions

Place of experimentation	
GPS Location	$6^o 24 N^o$ - $2^o 20$ E
Description	Laboratory E1510 / Polytechnic School of Abomey-Calavi
External conditions	
Average pressure	1,013 Bar
Average ambient temperature	27^o C
Getting measurement	
Step of measurement	01 min
Number of repetitions	03 repetition / test
Stopping criteria or limits	
Maximum battery voltage (charging)	3.6 V
Minimum battery voltage (discharging)	2.8 V
Maximum rate for charging	2 C
Maximum rate for discharging	5 C

From the data measured for each test, kinetic efficiency η_k, coulombic efficiency η_c and internal resistance r are determined by the following relationships:

for a charge or discharge test at a nC rate

$$\eta_k = \frac{60}{n \times \Delta t} \quad (1)$$

n: factor of charge or discharge rate

Δt : total test duration (mn)

$$\eta_c = \frac{\int_{\Delta t} V_{bat} I_{bat} dt}{36864} \quad (2)$$

V_{bat} : battery voltage (V)

I_{bat} : intensity of the current received in the charging phase or discharged in the discharge phase (A) for a load test

$$r = \frac{\sum_{t=1}^{t=\Delta t} \frac{V_{ch}(t) - V_{bat}(t)}{I_{bat}(t)}}{\Delta t} \tag{3}$$

V_{ch} : charging voltage at GPS - 3303 stabilized power supply (V) for a discharge test

$$r = \frac{\sum_{t=1}^{t=\Delta t} \frac{E - V_{bat}(t)}{I_{bat}(t)}}{\Delta t} \tag{4}$$

E : fe.m of the LFP cell (E = 3.3 V)

RESULTS AND DISCUSSION

Principal component analysis of these data yields the eigenvectors summarized in the following table 7:

Table 7. Eigenvectors associated with principal. Components

Variable	PC1	PC2	PC3	PC4	PC5
C-rate (.. C)	-0,651	-0,053	-0,078	-0,295	0,693
magnetic field (mT)	0,060	-0,724	0,433	-0,507	-0,166
kinetic efficiency	0,526	0,220	0,569	0,040	0,592
coulombic efficiency	0,303	-0,625	-0,449	0,425	0,367
internal resistance	0,452	0,182	-0,530	-0,688	0,086

Fig. 5 shows the principal component analysis (ACP) loading plot of C-rate, magnetic field, state, kinetic efficiency, coulombic efficiency, and internal resistance. The analysis of table 8 and Fig. 5 shows that kinetic efficiency, internal resistance, coulombic efficiency, and magnetic field are positively correlated with the first main component while the charging or discharging rate is negatively correlated. Moreover, the kinetic efficiency and internal resistance are positively correlated with the second main component, while coulombic efficiency, magnetic field, and charging or discharge rate are negatively correlated. It is then deduced that the first main component goes in the direction of the quality of use of the battery, in terms of conditions of use and performance resulting from the LFP battery.

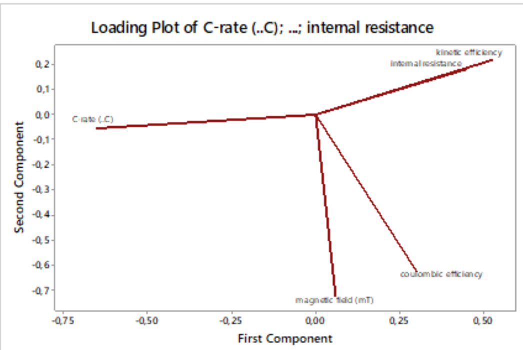


Fig. 5. ACP loading plot

The second main component goes in the direction of the resulting durability of the battery. The specific values associated with both main components make it possible to study them for the implementation of the ACP. Fig. 5 also shows that kinetic efficiency and internal resistance are strongly and positively correlated with each other; same as the correlation between magnetic field and coulombic efficiency. Moreover, the correlation between magnetic field and kinetic efficiency is negative but weak; same as the correlation between magnetic field and internal resistance. This announces that the magnetic field improves the overall performance of LFP batteries: it significantly increases the coulombic efficiency but slightly reduces the kinetic efficiency. This also announces that the magnetic field improves the durability of LFP batteries: it slightly reduces the internal resistance. The representation, according to the two main components of the score plots corresponding to the different tests, is shown in the following Fig. 6 .Fig. 6 shows a good homogeneity of the results according to the two main components. Pooling the results reveals the overall trends. The state of charge decreases overall with the first component. This is in accordance with many earlier resultts in the bibliography (Li , 2015) (Etacheri , 2011)(Zhang , 2010)(Alzieu, 2004)(Armand, 2001)(Rao, 2001)(Chiasserini , 1999) .Fig. 6.a show also that an increasingly high charging or discharging rate induces a poor quality of use of the LFP battery and reduces the resulting performance of them. The magnetic field decreases globally with the second component (confer Fig. 6.b).

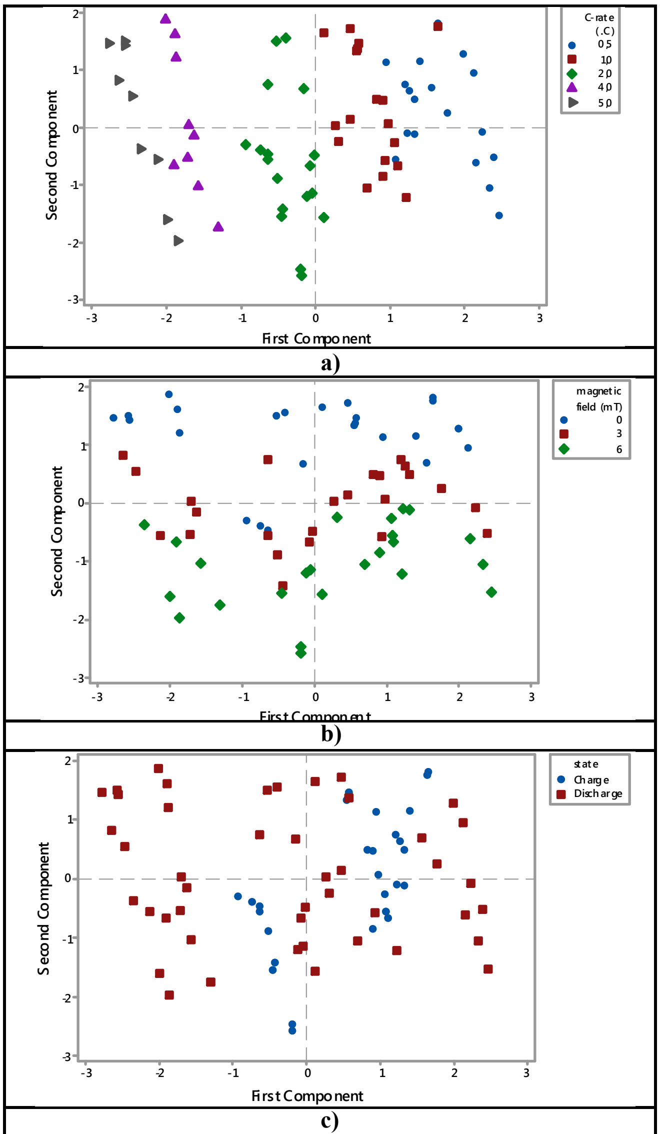


Fig. 6. a) ACP score plot for group C-rate; b) ACP score plot for group magnetic field ; c) ACP score plot for group state

This announces that the excessive increase in the magnetic field negatively impacts the durability of the LFP battery. The grouping of ACP score plots according to the process stage (charge or discharge) reveals that during the various tests carried out, the most important effects following the first component and the second component, were obtained during the discharge phase. Let us notify that we had not charged a battery at a rate above 2 C. The variation of LFP voltage and charging current for some test are shown in Fig. 7. The variation of LFP voltage and discharging current for some test are shown in Fig. 8. These Figure strengthen the precedent results about the advantages of the magnetic field on the performance and the durability of battery LFP.

The duration of charging LFP battery at the rate of 0.5 C is 120 min in the absence of a magnetic field (B = 0 mT), while it is 91 min for a magnetic field of 3 mT and 100 min for a magnetic field of 6 mT (confer Fig. 7.a and Fig. 7.b)

The evolution of the charging current (conferFig. 7.c) shows overall the two main phases of charging the LFP battery:

- The bulk phase, which corresponds to a constant current load
- The absorption phase which corresponds to a constant voltage load

A similars resultsareobtained for charging rate 1 C and 2 C. The particularity is that the charging current corresponding to the 2 C rate is lowered by the BMS integrated into the LFP - IFR 26650 battery. Indeed, this BMS limits the charging current of the na battery to a charging rate of about 1 C (confer Fig. 7.d).

Fig. 8 reveals that the magnetic field slightly increases the intensity of the current delivered by the battery during a discharge corresponding to a rate of 0.5 C. This leads to the reduction of the discharge time. For a discharge rate of 2 C, there is a significant increase induced by the magnetic field for the voltage, the intensity of the current delivered, and the discharge time. Discharge time is 31 min in the absence of a magnetic field (B = 0 mT), while it is 34 min for a magnetic field of 3 mT and 35 min for a magnetic field of 6 mT (confer Fig. 8.b). The tests with discharge rates of 1 C, 4 C, and 5 C lead to similar results (confer Fig. 9). Then, we retain that the magnetic field improves the performance of LFP batteries during discharge for rates greater than or equal to 1 C. With measured data we plot the Pareto diagram of normalized effects and the associated residues (confer**Error! Reference source not found.**). **Error! Reference source not found.**.a reveals that C-rate, magnetic field, and interaction between magnetic field and state are the three significant factors for the evaluation of kinetic efficiency, as their effects are

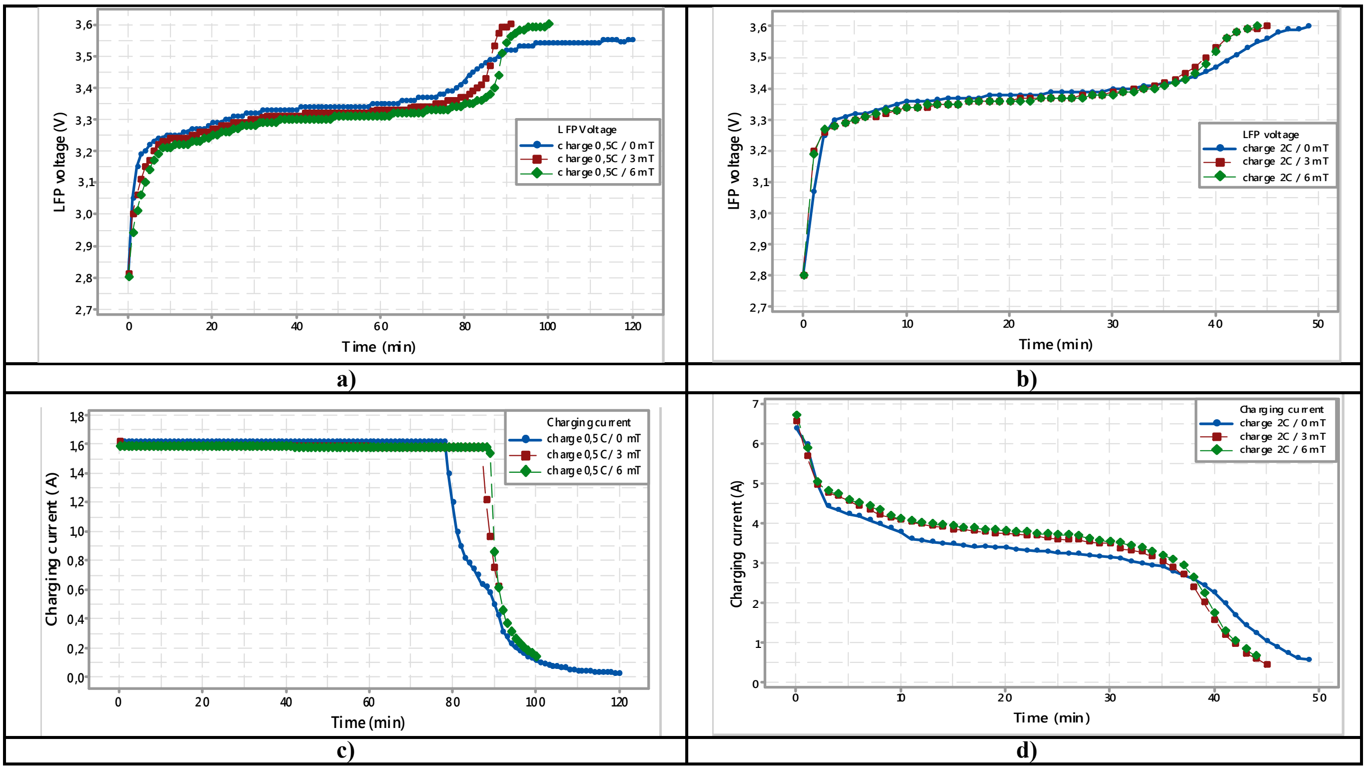
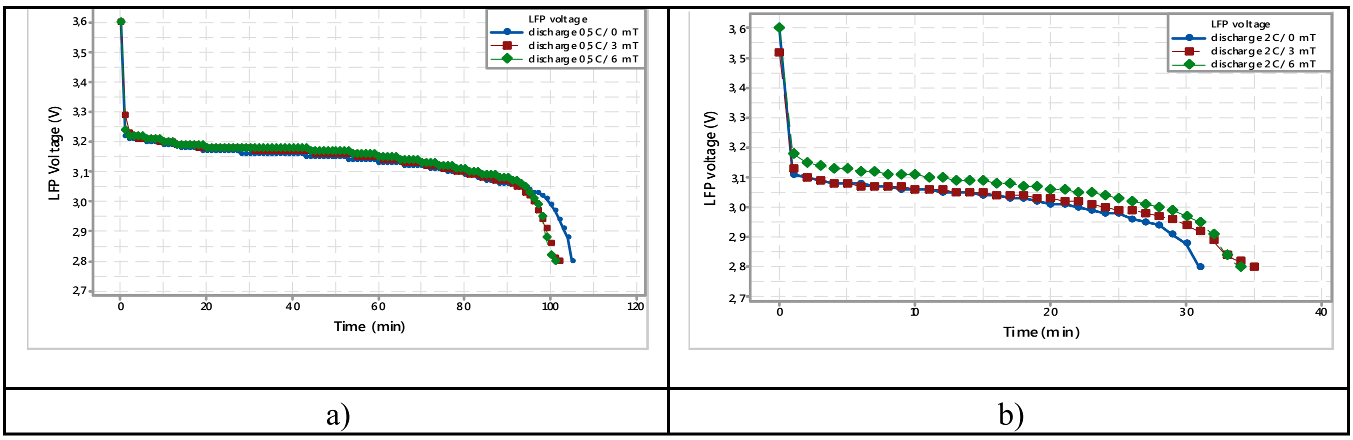


Fig. 7 : a) LFP voltage for charge rate (0.5 C) - Magnetic field (0 mT – 3 mT – 6 mT) ; b) LFP voltage for charge rate (2C) - Magnetic field (0 mT – 3 mT – 6 mT) ; c) Chargingcurrent for charge rate (0.5 C) - Magnetic field (0 mT – 3 mT – 6 mT) ; d) Charging current for charge rate (2C) - Magnetic field (0 mT – 3 mT – 6 mT)



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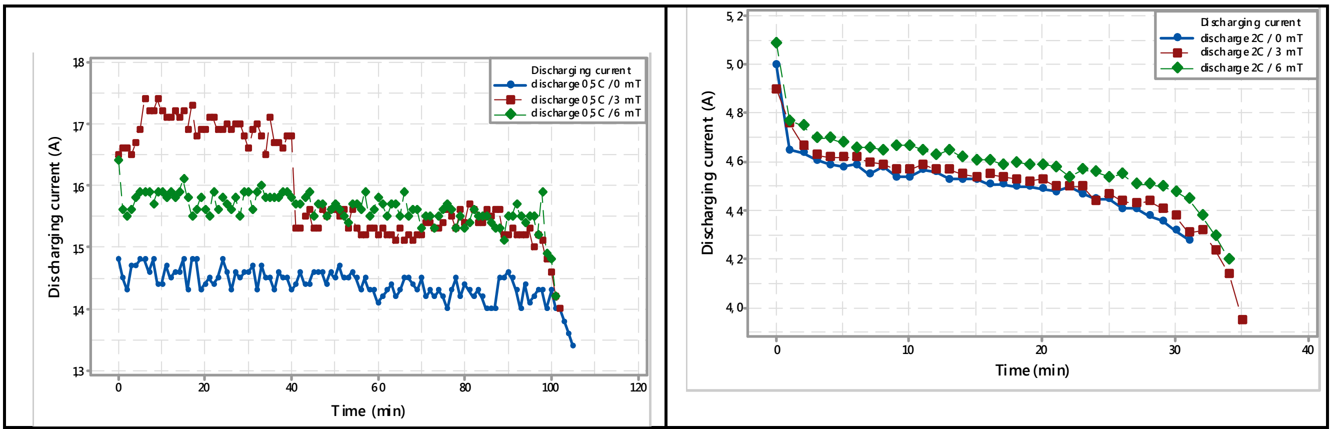


c) d)

Fig. 4 : a) LFP voltage for discharge rate (0.5 C)- Magnetic field (0 mT – 3 mT – 6 mT) ; b) LFP voltage for discharge rate (2 C)- Magnetic field (0 mT – 3 mT – 6 mT) ; c) Charging current for discharge rate (0.5 C)- Magnetic field (0 mT – 3 mT – 6 mT) ; d) Charging current for discharge rate (2 C)- Magnetic field (0 mT – 3 mT – 6 mT)

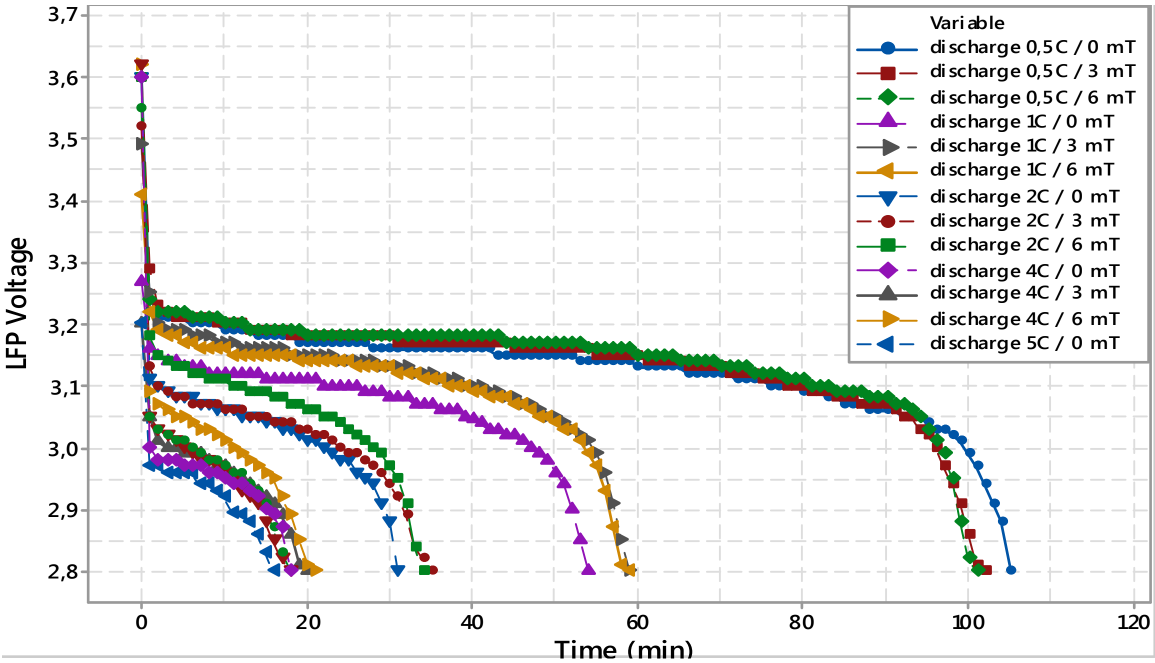
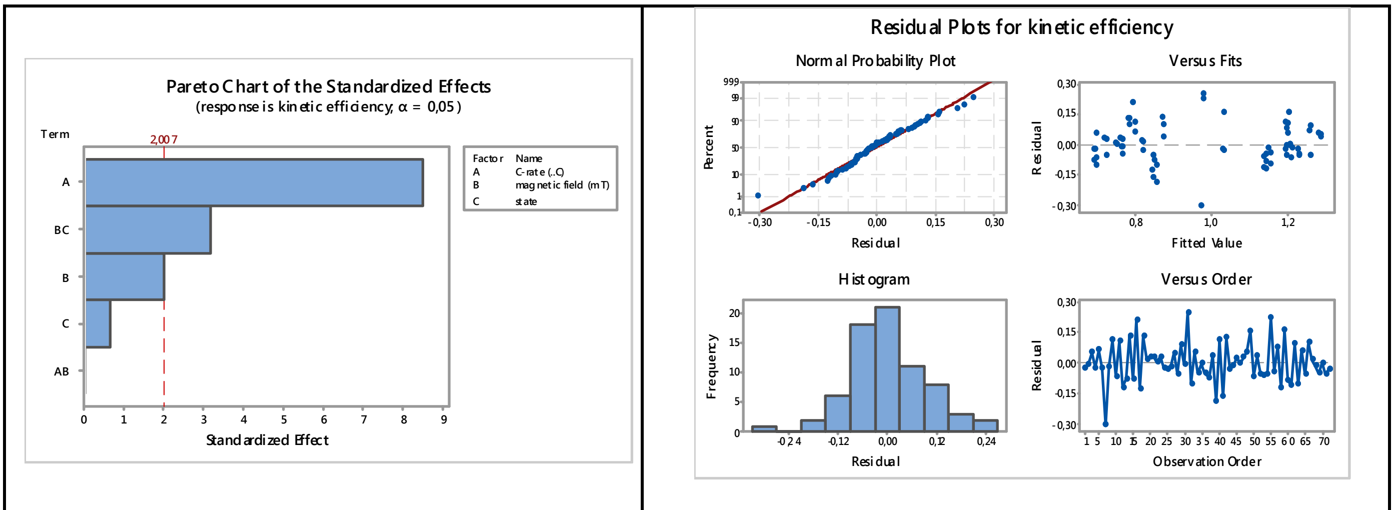
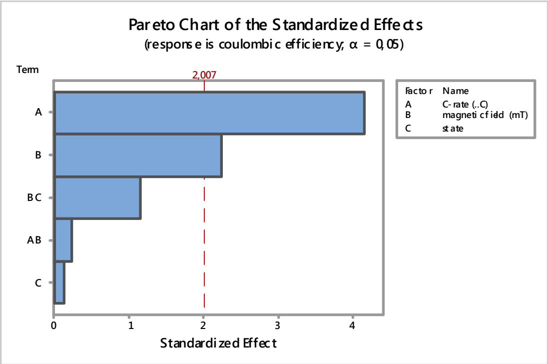


Fig. 9. LFP voltage for discharge rate (05 C – 1 C – 2 C – 4 C – 5 C)- Magnetic field (0 mT – 3 mT – 6 mT)

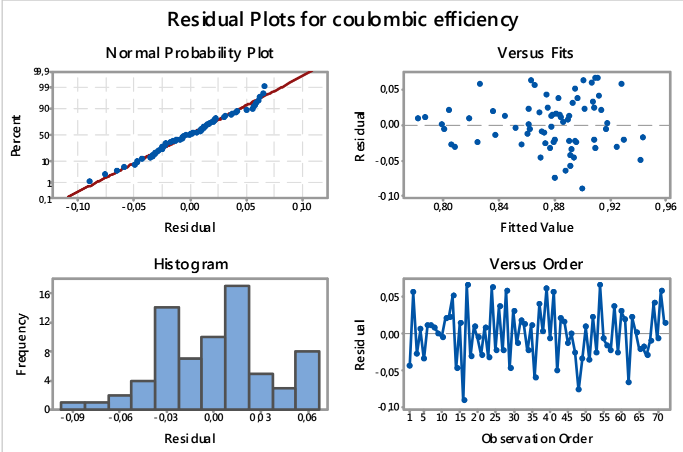


a) b)

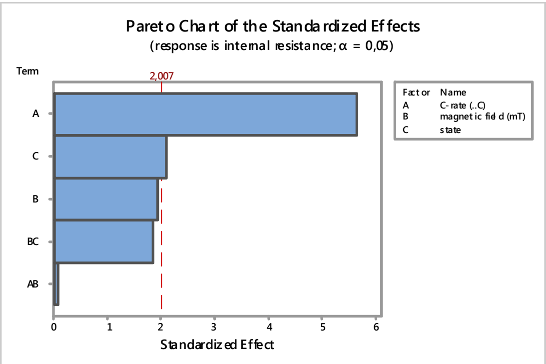
Continue…..



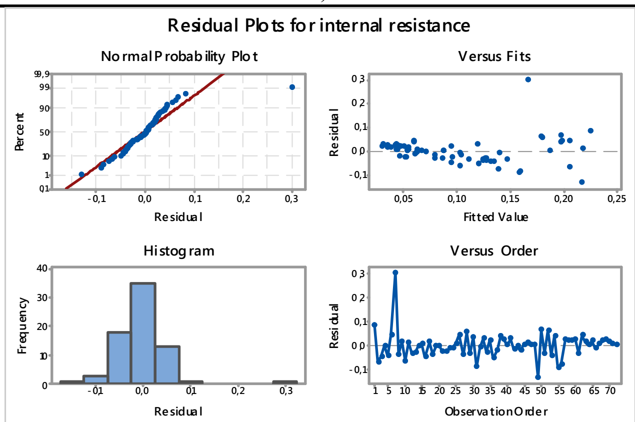
c)



d)

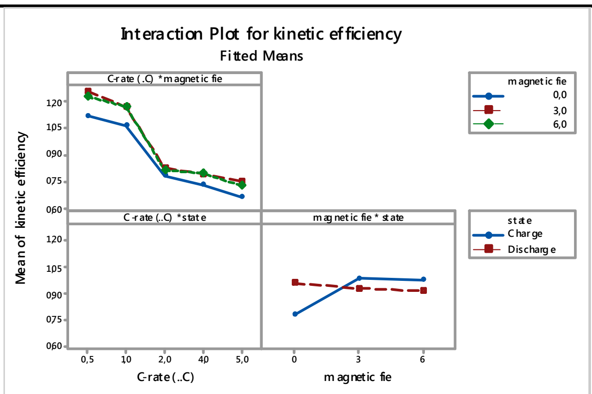


e)

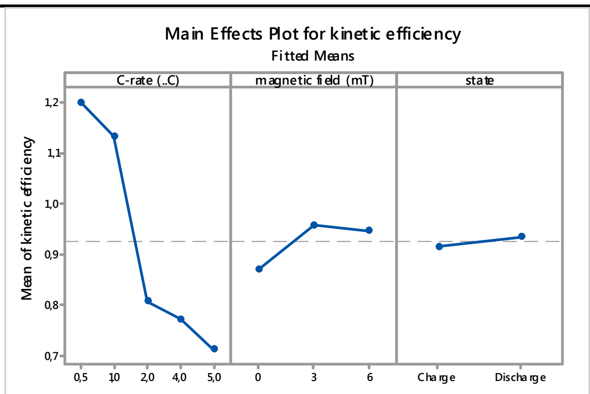


f)

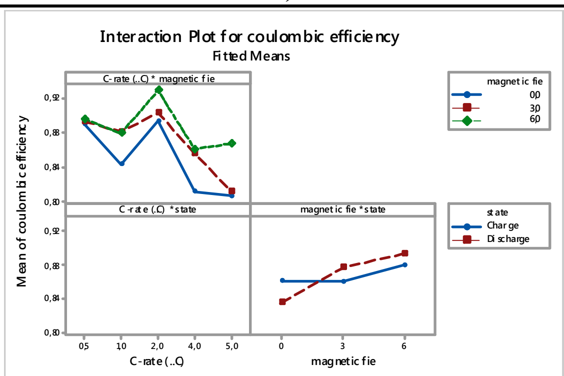
Fig. 10 : a) Pareto chart of standardized effects for kinetic efficiency; b) Residuals plot for kinetic efficiency; c) Pareto chart of standardized effects for coulombic efficiency; d) Residuals plot for coulombic efficiency; e) Pareto chart of standardized effects for internal resistance; f) Residuals plot for internal resistance



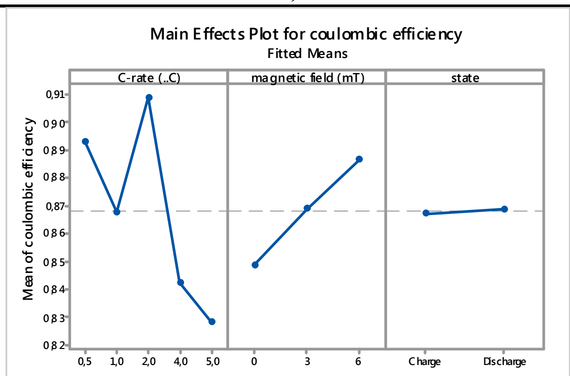
a)



b)



c)



d)

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Error! Reference source not found.b shows the

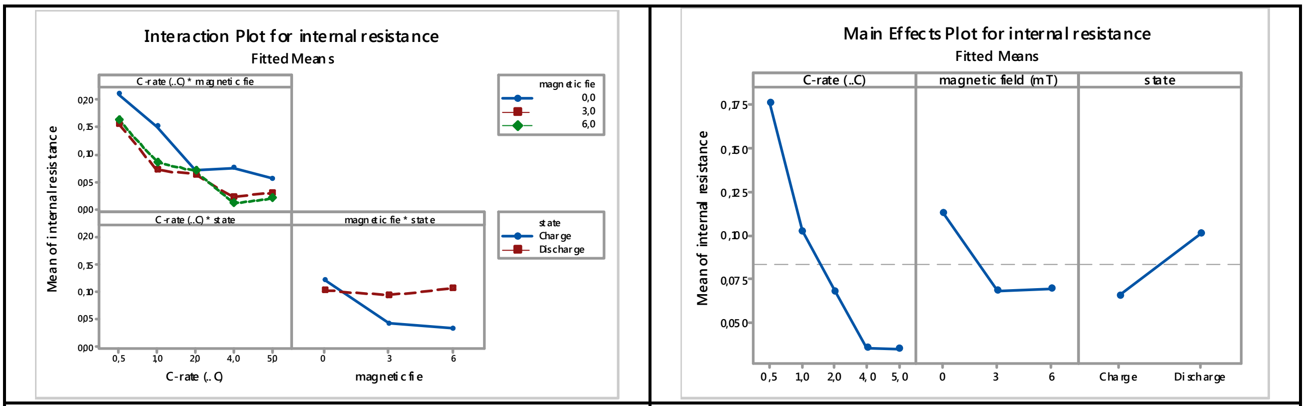

Fig. 11 : a) Interaction plot for kinetic efficiency; b) Main effects plot for kinetic efficiency; c) Interaction plot for coulombic efficiency; d) Main effects plot for coulombic efficiency; e) Interaction plot for internal resistance; f) Main effects plot for internal resistance

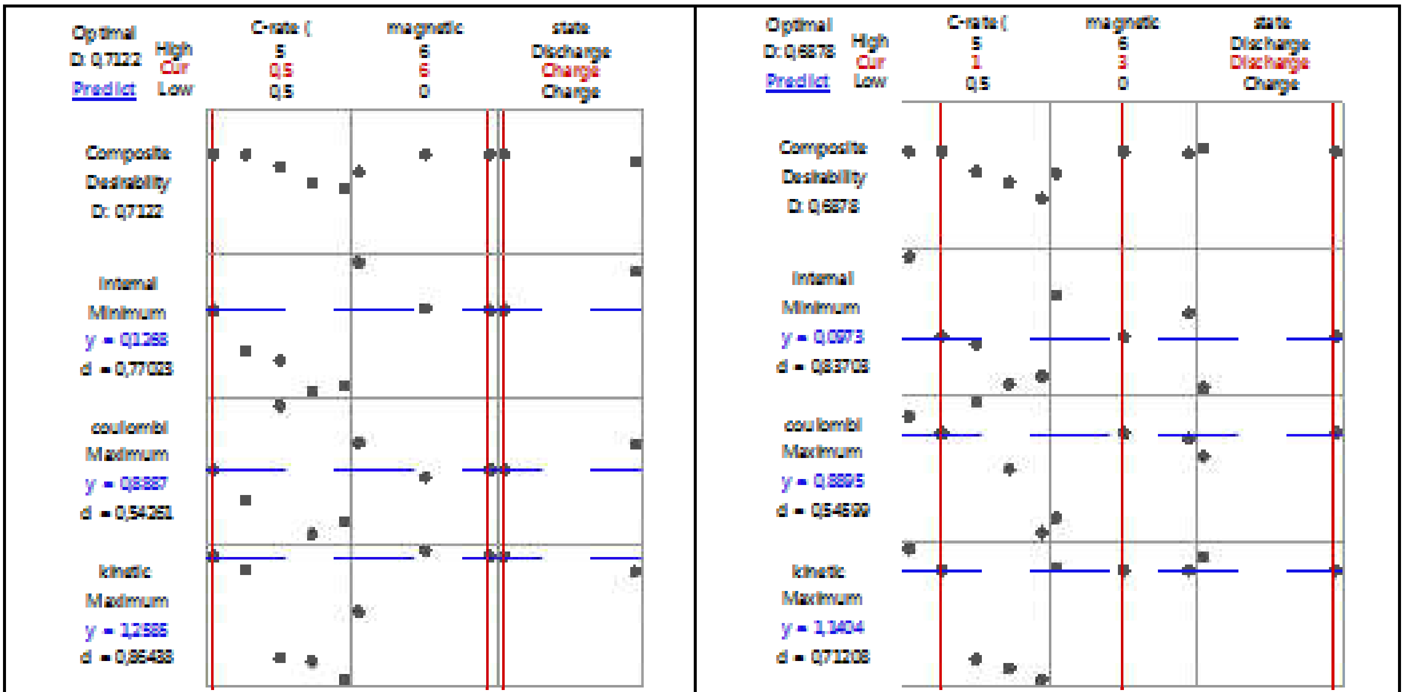

Fig. 12 : a) Search of the optimal solution during charging; b) Search of the optimal solution discharge

magnetic field are the two significant factors for the assessment of Coulomb efficiency, as their effects are beyond the significance limit for $\alpha = 0.05$. **Error! Reference source not found.**e shows that the C-rate and state are the two significant factors for the assessment of internal resistance, as their effects are beyond the significance limit for $\alpha = 0.05$. The associated residuals (confer **Error! Reference source not found.**b, **Error! Reference source not found.**d and **Error! Reference source not found.**f) show a good distribution of points along Henry's line. This indicates that the distribution of residuals is relatively normal. In order to understand the interactions between the various parameters, we plot the interaction diagram and the graph of the main effects for kinetic efficiency, coulombic efficiency and internal resistance. These plotting are shown in

recommend for common use of LFP batteries, a charging or discharging rate less than or equal to 1 C.

- The presence of the magnetic field leads to an increase in kinetic efficiency. For the battery studied LFP - IFR 26650, with a nominal voltage of 3.2 V and a nominal capacity of 3.2 Ah, the strength of the magnetic field that gives the best kinetic efficiency is equal to 3 mT.
- The kinetic efficiency obtained during battery discharge is slightly higher than that obtained during charging.

- The combined analysis of**Error! Reference source not found.**.c and **Error! Reference source not found.**.d shows the following results :
- The charging or discharging rate decreases overall with the coulombic efficiency. However, a 2 C rate gives on average, the best coulombic efficiency.
- The magnetic field significantly increases the coulombic efficiency. For the battery studied LFP - IFR 26650, with a mT against a value of 0.85 for a magnetic field of 0 mT.
- The coulombic efficiency obtained during the discharge of the battery is significantly higher than that obtained during charging.
- The combined analysis of **Error! Reference source not found.**.e and **Error! Reference source not found.**.f shows the following results :
- The increase in the charging or discharging rate leads to the decrease in the internal resistance of the battery. However, beyond a rate of 4 C becomes substantially zero.
- The presence of the magnetic field induces an overall decrease in the internal resistance of the LFP battery.
- The average internal resistance obtained during battery discharge is significantly higher than that obtained during charging.

Considering all previous results, it is important to research the optimal conditions to maximize the kinetic efficiency, maximize coulombic efficiency, and minimize internal resistance in the charging phase and in the discharging phase. The results of the optimization are shown in **Error! Reference source not found.**.

- During charging, establish a rate of 0.5 C and a magnetic field of 6 mT. This choice procurs the average 25 % of the increasing of kinetic efficiency, 5 % of the increase of Coulomb efficiency, and 58 % of reducing of internal battery resistance compared to the choice of a charge rate of 0.5 C in the absence of a magnetic field (B = 0 mT).
- During discharge, we recommend a rate of 1 C and a magnetic field of 3 mT. This choice procurs an average 2.6 % of increasing of kinetic efficiency, 8.4 % of increasing of coulombic efficiency, and 26 % reduction of internal battery resistance compared to a choice of discharge rate of 1 C in the absence of a magnetic field (B = 0 mT).

CONCLUSION

The current global energy crisis has highlighted the urgency, as well as the benefits of an accelerated transition to cheaper and cleaner energy sources. The use of these energy sources usually requires a storage system of which one of the most widespread technologies nowadays is the $LiFePO_4$ battery. Several works have been made to improve the performance, durability, and cost of these batteries. The present work focused on improving the performance and durability of $LiFePO_4$ batteries through the application of a constant magnetic field. To do this, we defined three parameters: kinetic efficiency and coulombic efficiency for performance assessment, then internal resistance and internal resistance for durability assessment. With an experimental device consisting globally of a Helmholtz coil, a magnetic damping box, a discharge bench, and a data acquisition chain, we tested the $LiFePO_4$ - IFR 26650 battery with a nominal voltage of 3.2 V and a nominal capacity of 3.2 Ah. We therefore defined three factors: the charging or discharging rate (0.5 C – 1 C – 2 C – 4 C – 5 C), the magnetic field (0 mT – 3 mT – 6 mT) and the state of the process (Charge – Discharge). From the complete factorial design, we built a design of experiments and then conducted the different tests. The analysis of these results leads to several conclusions, the most important of which are as follows. An increasingly high charging or discharging rate leads to a decrease in kinetic efficiency, coulombic efficiency, and internal resistance. Thus, increasing the rate, reduces the overall performance of the LFP battery and increases its durability. The magnetic field increases the kinetic efficiency, coulombic efficiency and decreases the internal resistance. Thus, the magnetic field improves the performance and durability of LFP batteries. The kinetic efficiency, coulombic efficiency, and internal resistance obtained during battery discharge are higher than those obtained during charging. Thus, the best performance of LFP batteries is obtained during the discharge phase.

We had finished the present work by searching the optimal conditions of use of the LFP battery studied. These conditions can be summarized as follows:

- during charging, establish a rate of 0.5 C and a magnetic field of 6 mT.
- During discharge, we recommend a rate of 1 C and a magnetic field of 3 mT.

Optimal conditions during charging procurs average 25 % of increasing of kinetic efficiency, 5% of increasing of Coulomb efficiency, and 58 % of reducing of internal resistance compared to a charge rate of 0.5 C in the absence of a magnetic field (B = 0 mT). Optimal conditions during discharge procurs average 2.6 % of increasing of kinetic efficiency, 8.4 % of increasing of Coulomb efficiency, and 26 % of reducing of internal battery resistance compared to a discharge rate of 1 C in the absence of a magnetic field (B = 0 mT).

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