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System for repetitive battery charge and discharge tests for battery life analysis

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Abstract.
Lead-acid batteries are and will still be widely used to power various electrical systems. Unfortunately, these are found for most of the time at rest and by the time they are called to work, they could be out of order, creating real problems for critical infrastructures. The work aims to lead to the construction of a test system for verifying the performance and life of UPS batteries starting from the analysis of different batteries with equivalent characteristics. The first step serves to determine a standardization of the work and of the system to obtain a useful reference for the comparison and repetition of subsequent tests.

Key words. Battery test; battery life; lead-acid battery; SFRA test.

1. Introduction

A battery is an electrochemical device formed by a series of galvanic cells, connected to each other in series or in parallel, which allows energy exchange through the conversion of chemical energy into electrical energy. The functioning of the battery is regulated by a spontaneous redox reaction which allows the exchange of electrons between the chemical species involved and which have a different tendency to release electrons.
Secondary batteries, or accumulators of electric charge, in addition to having a discharging action, can be subjected, through the chargers, to a period of charge during the supply of electricity to the battery. The charging process is called electrolysis, in this way, there is an inversion of the poles allowing the restoration of chemical energy. Through this operation the chemical agents are recomposed and once the charging phase is complete, the battery is able to operate a new discharge process. Secondary cells can be used in series, in parallel, or as a combination of both, to achieve the required voltage and capacity. The only limitation is that each cell must be similar in voltage, capacity and chemical composition.
Secondary batteries can be classified according to the type of construction. The most common batteries are lead-acid, nickel-cadmium, nickel-metal hydride and lithium-ion batteries.
Lead-acid batteries were the first to be developed in 1859 and still remain the most common type of rechargeable batteries used.
Lead-acid batteries are still widely used in many sectors and will always be widely used in many applications where there is no need for high energy density and instead it is preferable to use less expensive batteries. For example in hospitals, the numerous UPS groups power all critical applications such as datacenters and life-saving machines. In these applications, system reliability is of utmost importance and in many cases these batteries have shown severe degradation after a few years[1].
Each battery is made up of 3 or 6 individual cells, each with a nominal voltage of approximately 2 V which supply a voltage of 6 and 12 V to the battery respectively. These batteries are then connected together to make a group of the required voltage and capacity. Each element consists of a "tray" containing an active lead plate for the anode; a lead dioxide plate for the cathode and an electrolyte solution consisting of sulfuric acid and distilled water.

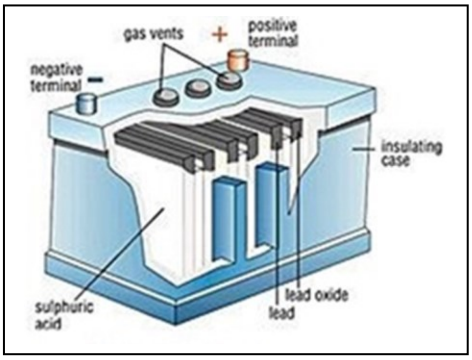

Fig. 1. Lead acid battery

During the discharge, the anode undergoes an oxidation reaction of the lead metal in Pb_2^+ which, when combined with the ions of the electrolytic solution, becomes $PbSO_4^{--}$ as can be seen from the following half reaction:

$$Pb + SO_4^{2-} \leftrightarrow PbSO_4 + 2e^- \quad (1)$$

where "←" for charge and "→" for discharge.
At the positive electrode, the reduction of lead peroxide occurs, the lead in the Pb_4^{++} state reacts with the ions of the electrolyte solution and precipitates as PbSO4 according to the following reaction:

$$PbO_2 + 2e^- + H_2SO_4 + 2H^+ \leftrightarrow PbSO_4 + 2H_2O \quad (2)$$

The final reaction is:

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O \quad (3)$$

The different types of lead batteries are classified also according to the use made of them. Lead-acid batteries can be used in buffer mode, in cyclical use, for the accumulation of renewable energies for starting motor vehicles or for traction of small electric vehicles.
The Valve Regulated Lead Acid (VRLA) or Sealed Lead Acid (SLA) can be divided into 2 types: AGM, suitable for fast charges thanks to the lower internal resistance; GEL, suitable for constant current applications and resistant to extreme temperatures and temperatures.
Batteries suitable for deep discharge contain fewer plates but much thicker than its peers. The reduction of the surface of the plate exposed to the electrolyte limits the passing current but increases the amount of charge [2].
For standby operation as in UPS, the AGM type is predominantly used. The fundamental characteristics of a battery that must be taken into account are:

- The electrochemical potential or voltage, expressed in Volt [V], It is possible to distinguish an open circuit voltage (OCV), which is 5-7% higher than the rated voltage with which the batteries are normally marked, and a closed circuit voltage (CCV) which represents the operating voltage.
- The capacity of a battery measured in amp-hours (Ah). It quantifies the life of a battery in hours at a given discharge current.
- The rate at which the electric charge is exchanged between the electrodes is referred to as the c-rate. The base value is "C" or "1C" and is calculated as the current required to charge or discharge a battery at nominal capacity in one hour.
- Depth of Discharge (DoD) expressed as a percentage of the total battery capacity.

The internal resistance of the batteries depends on the size of the battery, its chemical properties, temperature, age and the current supplied [3]. The measurement of the internal resistance of a battery is an indication of its condition because with aging it tends to increase, causing a decrease in voltage up to a value for which the battery becomes unusable.
The temperature has a significant effect on the battery life and on the voltage characteristic since at temperatures rather lower than the ambient temperature (20 ° C) there is a reduction in chemical activity and an increase in internal resistance. At higher temperatures, chemical activity increases and this causes a significant reduction in capacity.
As the temperature increases, the self-discharge also accelerates. The self-discharge law (loss of capacity over time as a result of parasitic chemical reactions) is a linear function with time as it can be faster at first and then slow down.
In general, the test carried out consists in alternating discharge phases and charging phases of the various batteries interspersed with measurements of the battery parameters, through the FLUKE BT521, and data acquisition via SFRA tests to obtain information on the internal state of the battery. The discharge phase as well as the charge phase is managed through the LabVIEW system.

2. Battery life cycle

The duration of a battery is a parameter that is usually measured in number of cycles, that is the number of charge-discharge cycles, that the battery is able to perform before its nominal capacity falls below 80% of its initial capacity. Each charge-discharge cycle involves a slow internal deterioration of the cell. This can be the result of unwanted chemical actions that change the morphology of the particles that make up the electrodes, leading to a reduction in capacity or an increase in internal resistance. This parameter is extremely variable and is largely influenced by the operating conditions [4].
The major reason that causes both loss of capacity and malfunction of lead-acid batteries is the sulfation of the battery.
In addition to the flow of electrons during the discharge phase, another change that occurs inside the battery concerns the relationship between sulfuric acid and water in the electrolyte. If the battery does not work properly or is left discharged for a long time, a reaction by-product, lead sulfate, is generated [5]. Lead sulfate forms a patina on the plates inside each cell reducing their active surfaces. The decrease in the area available for energy production causes a consequent decrease in amperage or current and incurs a reduction in the internal resistance of the battery, compromising its functionality. This phenomenon is better known as Sulfation. If the discharge process continues, more and more lead sulfate is deposited on the cell plates, until after a certain period the current generation process becomes impossible. The sulfate deposits on the plates are the reason why a battery cannot supply energy for an infinite time. In fact, a prolonged discharge causes harmful sulfation and the battery may no longer be recoverable, even if charged for a long time.
The charging process becomes inefficient because the lead sulphate crystals depositing on the active surfaces cause the battery to show a higher voltage level than it actually has, not allowing recharging even if the battery is actually discharged.
During the recharging phase of a lead-acid battery, the reverse process takes place as previously described. By connecting a current generator to the two electrodes of the battery, the electrons move from the positive to the negative electrode thanks to an external force that does a job, the electromotive force of the generator goes to counteract the normal flow and to impress the current in a direction opposite to what it would normally have in the discharge phase. On the negative electrode the influx of electrons causes the reduction of the Pb_2^+ ions with the deposition on the electrode itself of metallic lead (Pb) and the formation of $SO4^{--}$ ions consequent to the breakdown

of the lead sulphate that was formed in the phase of download. On the positive electrode the subtraction of electrons causes the oxidation of the Pb_2^+ ions into Pb_4^+ ions which, reacting with the O_2^- ions present in the solution for the electrolytic dissociation of the water, deposit again lead dioxide (PbO_2) on the positive electrode, releasing in solution H^+ ions which balance the SO_4^- ions obtained from the dissociation of lead sulphate, consequently the initial concentration of sulfuric acid in the electrolyte solution is gradually restored with the simultaneous disappearance of the lead sulphate. The recharging process can be considered completed when all the lead sulphate molecules (PbSO4) formed during the discharge have been broken down again, restoring the initial concentration of sulfuric acid in the electrolyte. If, once this defined condition of completed charge is reached, one continues to supply energy to the battery, there is no further increase in charge but the energy supplied only produces further electrolysis of the water molecules present in the solution with the formation of hydrogen H_2 at this point. and Oxygen O_2 in the molecular state (gas) this extremely dangerous condition as the mixture of the two gases at high concentrations can be explosive.

It is also important that the charging process does not last longer than necessary as in addition to the formation of dangerous gases there is also the, not secondary, the effect of the loss of water from the solution with the consequent variation of the density and level of the electrolyte.

The lead element is fully charged if in open circuit 2.13 V/el are measured at its poles, vice versa it is to be considered completely discharged when there are 1.6 V/el at the poles.

3. Charge and Discharge test system

The discharge characteristic graph relates voltage values, currents and discharge times. Each curve is characterized by a different C-rate since each curve is an indicator of a different current value with which the discharge can be carried out. The lower the current value with which the discharge is carried out, the higher the curve and the greater the energy supplied by the battery during the process [6]. Through this graph, it is, therefore, possible to see the behavior of the battery at different discharge currents and it is possible to read the voltage value at any time.

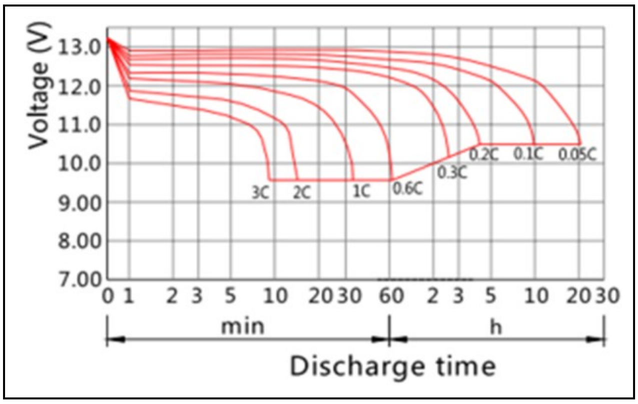

Fig. 2. Discharge characteristics (25°C) of SELCO 3DS BS 12-7 UPS battery

Agilent's 600W electronic charging system called N3301A was used to discharge the battery. It is a "resistance simulator" which, applied to the output of the battery under test, allows you to apply a load resistance and deliver the desired current.

The instrument contains two modules which can also be connected in series depending on the required power. It has three operating modes selectable from the front panel: i) Constant Current mode, ii) Constant Voltage mode and iii) Constant Resistance mode.

Figure 3 represents the battery charge curve. It is a curve that relates the charging time with the voltage and current value [7]. Through the intersection between the different curves present in the graph, it is possible to define the battery charge level but also to define the charge modes of the same.

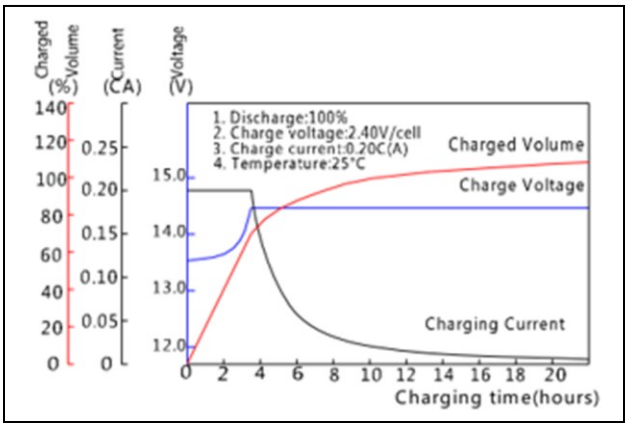

Fig. 3. Charge characteristics (25°C) of SELCO 3DS BS 12-7 UPS battery

Most commercial chargers for lead-acid batteries start charging initially with constant current, ending with constant voltage regardless of the actual state of charge of the battery, the temperature of the battery and its variation over time or the density of the electrolyte and of its variation over time [8]. On the other hand, most of the power supplies mounted inside the alarm and burglar-alarm control units are simple charge maintainers with constant voltage and are not very suitable for recharging the lead acid battery after a lasting discharge.

In fact, figure 4 shows the charge curve of a battery discharged up to 9.98V with a normal charge maintainer.

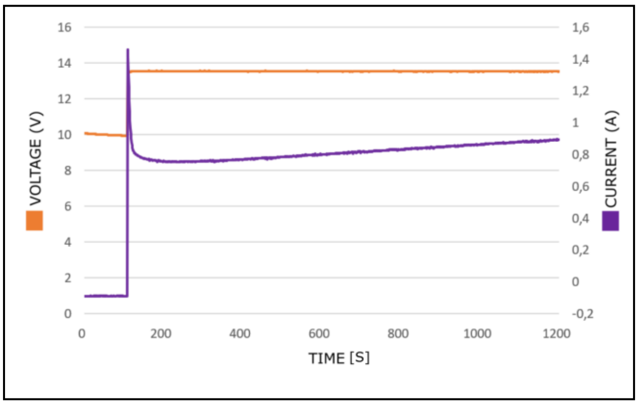

Fig. 4. Charging an UPS battery using a charge maintainer

It is noted how this power supply immediately fixes the voltage at 13.55V and the uncontrolled current in some

periods also exceeds the maximum battery charge current suggested by the manufacturer's specifications.
If the battery often works with deep discharges, repeated recharging with charge maintainer leads to a fast degradation of the battery.
The KEPCO BOP 72-6M power supply controlled by the "current programming input" was used to follow the charge profile. The hall effect transducers LEM LV 25-P and LEM LA 25-NP were used to measure the charging voltage and current, connected to the analog input ACH5 and ACH7 of the National instrument BCN 2120 board.
The control of the power supply was carried out in Labview by means of a counter-reacted cycle which reads the output voltage and current from the power supply to the battery and manages the power supply input through the analog output of the National instrument BCN 2120.
A part of the Labview cycle that manages the recharge is shown in fig. 5. It shows the while loop which reads the voltage and current inputs from the BNC 2120 board and based on them adjusts the analog output until the battery is charged.

4. Tests

The test battery used is the SELCO 3DS BS 12-7 UPS which has the following nominal characteristics [9]:

- Nominal voltage: 12V;
- Capacity: 7.2 Ah;
- Internal resistance: 28mΩ.

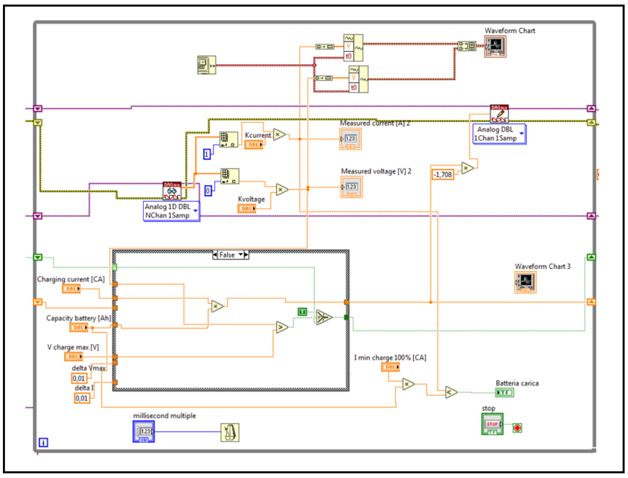

Fig. 5. Charging while loop.

The discharge characteristics of the battery, i.e. the current or power value, at which the discharge can be carried out without irreparably damaging the battery, can be deduced from table 1.
The table relates the discharge current with the discharge time, i.e. given the working time and the final allowable voltage F.V. indicates the maximum discharge current value
The test carried out on the sample battery involves alternating charging and discharging phases, each of which is followed by the SFRA analysis [10, 11].
The discharge phase is conducted at a current of 12 A for a maximum time of 5 minutes while the charging phase is instead operated as the previous test, there is a first part of the charge carried out at constant current and equal to 1.4.

Table I. – Constant current and power discharge characteristics of SELCO 3DS BS 12-7 UPS battery

Constant Current Discharge Characteristics (A, 25℃)

F.V/TIME	5min	10min	15min	30min	60min	2h	3h	4h	5h	10h	20h
9.60V	27.4	17.3	13.7	7.63	4.68	2.56	1.84	1.47	1.25	0.68	0.37
9.90V	26.5	16.8	13.4	7.48	4.61	2.54	1.83	1.46	1.24	0.68	0.36
10.2V	25.4	16.1	12.9	7.25	4.49	2.52	1.81	1.45	1.23	0.67	0.36
10.5V	24.4	15.4	12.4	7.07	4.40	2.48	1.80	1.44	1.22	0.67	0.36
10.8V	23.0	14.5	11.8	6.82	4.27	2.42	1.75	1.40	1.19	0.66	0.35

Constant Power Discharge Characteristics (Watt, 25℃)

F.V/TIME	5min	10min	15min	30min	60min	2h	3h	4h	5h	10h	20h
9.60V	305	195	156	87.5	54.2	29.9	21.8	17.5	14.9	8.16	4.38
9.90V	296	189	152	85.7	53.4	29.7	21.7	17.4	14.8	8.12	4.37
10.2V	284	181	147	83.1	52.0	29.5	21.5	17.3	14.7	8.08	4.35
10.5V	272	173	142	81.1	51.0	29.0	21.4	17.2	14.6	8.04	4.32
10.8V	256	164	134	78.1	49.4	28.3	20.7	16.6	14.2	7.87	4.23

Note: The above characteristics data can be obtained within three charge/discharge cycles.

A until the battery is brought to the maximum allowable voltage of 14.5 V; once this voltage value is reached, the charge proceeds at constant voltage and variable current in a decreasing way. The values collected via the fluke BT521 are entered in the following table.

Table II. – Measurement of internal resistance and battery voltage, ambient temperature and humidity measured at the end of the cycle

TEST AFTER:	TEST NUMBER	INTERNAL RESISTANCE (mΩ)	RELATIVE HUMIDITY (%)	VOLTAGE (V_{DC})	TEMPERATURE (°C)
OPEN CIRCUIT	1	40,9	46,4	12,9	14,5
DISCHARGE 1	2	54,5	43,4	12,39	15,4
CHARGE 1	3	36,6	42	13,35	16,5
DISCHARGE 2	4	51,6	41,2	12,53	17,8
CHARGE 2	5	36,6	40,1	13,24	18
DISCHARGE 3	6	52	39,2	12,46	18,8
CHARGE 3	7	36,3	38,6	13,26	19,1
DISCHARGE 4	8	51,4	39,3	12,49	19,8
CHARGE 4	9	36,1	38,8	13,21	19,9
DISCHARGE 5	10	51,1	38,6	12,5	19,9

The discharge lasts for 5 minutes while the charge lasts approximately one hour
Comparing the fig.6 graph obtained following the test of charge with that of the datasheet (fig. 3) it can be seen that they have a similar trend.

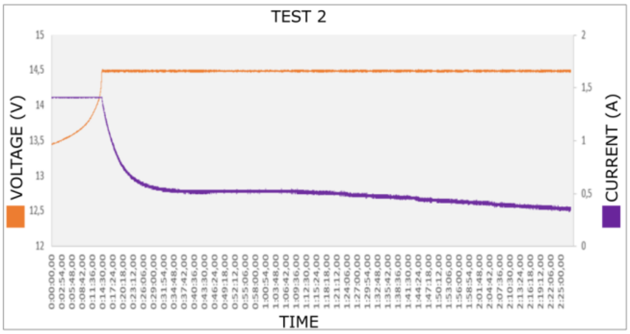

Fig. 6. Charge characteristics (25°C) of SELCO 3DS BS 12-7 UPS battery

From the comparison between the curves obtained from the SFRA analysis (fig. 7), a complete overlap of the curves can be seen.

5. Conclusion

Batteries are the ultimate defense systems against total blackouts in buildings and therefore their breakdown could be disastrous for critical applications such as those applied in medical, communication or defense locations.
Currently, to avoid the inactivity of UPS groups, only a battery change policy is implemented on a regular basis without checking the status of the battery or only intervenes with the replacement of the faulty battery after

having ascertained that the system does not work. Moreover, as seen, the charge maintainers are not suitable for recharging batteries with deep discharges and this could wear down the batteries, shortening their life.

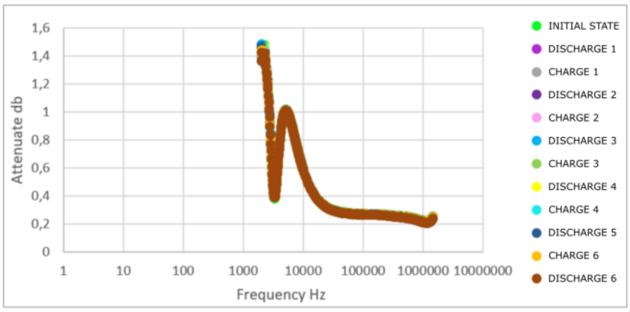

Fig. 7. Comparison between the curves obtained from the SFRA analysis after charge/discharge cicles

Therefore, it is natural to try to find alternative methods to automatically analyze the batteries during their natural functioning, and in the installation box. The SFRA method, already widely used, for the continuous verification of other electrical components can also be applied as a battery verification tool.
The first step of this work was shown in this paper; where the authors have automated the charge/discharge cycle of the batteries together with the continuous data analysis in order to detect variations in the parameters during the life of the battery.
The appropriate variation of the input parameters from the program allows to obtain a series of charge / discharge cycles, even deep ones, which can be modeled on the characteristics of the batteries under test.
Data analysis is long and time-consuming. Furthermore, battery life is reduced after numerous cycles. For this, only the first experimental results have been shown in this paper.

References

[1] F. Al-Jabarti, A. Al-Mutairi and A. Al-Harbi, "Data Center Flooded Lead Acid Battery Early Degradation Causes, Analysis, and Mitigation," 2018 IEEE International Telecommunications Energy Conference (INTELEC), 2018, pp. 1-4, doi: 10.1109/INTLEC.2018.8612300.

[2] Types of Lead Acid Batteries, March 1, 2020 https://federalbatteries.com.au/news/types-lead-acid-batteries

[3] Stefano Cordiner, Vincenzo Mulone, Studio su prove di invecchiamento e degrado di celle al litio, ENEA, Report RdS/PAR2014/180

[4] J. -C. Hwang, J. -C. Chen, J. -S. Pan and Y. -C. Huang, "A SCADA system for on-line battery early faults precaution," 2009 IEEE International Symposium on Industrial Electronics, 2009, pp. 65-69, doi: 10.1109/ISIE.2009.5213129.

[5] Delgado-Sanchez, J.-M., Lillo-Bravo, I., "Influence of Degradation Processes in Lead–Acid Batteries on the Technoeconomic Analysis of Photovoltaic Systems", Energies 2020, 13, 4075, https://doi.org/10.3390/en13164075

[6] D. Gies, "Safety of electrical equipment containing lead acid batteries," 2009 IEEE Symposium on Product Compliance Engineering, 2009, pp. 1-7, doi: 10.1109/PSES.2009.5356022.

[7] Yuasa, "Battery Characteristics & Fault Diagnosis", Site: https://www.yuasa.co.uk/info/technical/battery-characteristics-fault-diagnosis/, visited on 24 february 2022.

[8] J. Alvarez, J. Marcos, A. Lago, A. A. Nogueiras, J. Doval and C. M. Penalver, "A fully digital smart and fast lead-acid battery charge system," IEEE 34th Annual Conference on Power Electronics Specialist, 2003. PESC '03., 2003, pp. 913-917 vol.2, doi: 10.1109/PESC.2003.1218177.

[9] PowerStream, Lead Acid Battery Charging Basics and Chargers, October 22, 2021, Site: https://www.powerstream.com/SLA.htm, visited on 24 february 2022

[10] G. Bucci, F. Ciancetta, A. Fioravanti, E. Fiorucci, S. Mari, A. Silvestri, "Online sweep frequency analysis testing on UPS for resilience", Measurement: Sensors, Volume 18, 2021, 100079, ISSN 2665-9174, https://doi.org/10.1016/j.measen.2021.100079.

[11] G. Bucci, F. Ciancetta, A. Fioravanti, E. Fiorucci, S. Mari and A. Prudenzi, "Fast testing platform for the isolation transformer", RE&PQJ, Volume No.19, September 2021, https://doi.org/10.24084/repqj19.236.