SHUT DOWN OF DCS DUE TO THE *COUP DE FOUET* EFFECT OF LEAD ACID BATTERIES

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ABSTRACT

The Gabriel Passos Refinery, which is part of the PETROBRAS holding company, is located in the city of Betim (Minas Gerais – Brazil). This refinery is served by local electrical utility company by means of two 138 kV transmission lines.

The control and monitoring of process variables in a utility substation are performed by a DCS (Digital Control System) and the power supply comes from a UPS (Uninterruptible Power Supply).

Due to the occurrence of an event in the substation, the two lines that feed the refinery were shut down, leading to a blackout of the electrical system.

In the shutdown event, the UPS lost the power supply from the static switch and the rectifier. At this moment, the only source of energy to feed the loads was the battery stack. However, some UPS turned off, leaving their loads without power.

After normalization of the electrical system, the refinery maintenance team looked for the reasons of the outage of the UPS. The first test made was the battery capacity measurement resulting in 85% of autonomy. At a first glance, the cause of the UPS shutdown was not identified, because the battery stack had enough charge to supply the loads during the blackout. Several tests have been performed afterwards on the UPS. One of them consisted of an oscillography at the moment that the battery stack started to feed the critical loads. At this test the cause of the shutdown was established and it was verified to be related with the intrinsic effect of lead acid batteries called *Coup de Fouet*.

This paper aims to show the risks of this effect for critical systems, the solution to the problem and the maintenance procedures for coexisting with it.

FOREWORD

This paper discusses a case study of the consequences of a lack of energy from the utilities in the electric system of an oil refinery that lead to the loss of control of the production. It was observed that some process controllers (DCS) fed by UPS failed when they should continue to be fed by the batteries.

The batteries were submitted to discharge capacity tests. It was observed that the batteries capacity was beyond 85% = superior to the ratings established in standards. As the measured values did not justify the failure of the UPS, the maintenance team decided to carry out tests in order to make an oscillogram of the instant when the critical load was switched to the batteries. The voltage dip observed had a sufficient depth in order to reach the inverter shut down voltage. It was also observed that the voltage dip had a recovery time in the order of tens of milliseconds. Therefore, it was inferred that the cause of the shut down of the inverters was the *coup de fouet* effect.

The *coup de fouet* effect is a lead acid intrinsic phenomenon for which there is not sufficient available information in the technical literature. It was also observed that the design of the UPS dc link does not consider the compensation for this phenomenon.

After the identification of the *coup de fouet* effect, routines to detect this effect were included in the refinery maintenance proceedings. It was also proposed a more profound study of the *coup de fouet* effect in comparison to the battery conductance and life expectancy.

CASE STUDY OF THE GABRIEL PASSOS REFINERY

PETROBRAS is a State-Controlled oil holding company of Brazil with 13 refineries distributed over the Brazilian territory. The Gabriel Passos refinery (REGAP) is situated in the Minas Gerais state. The refinery has a processing capacity of 150,000 barrels a day.

The Refinery Electric System

The refinery electric system is fed by two 138kV transmission lines, by means of the local utility, in closed ring. Four transformers feed its own bar as shown in figure 1. The refinery does not have its own electric generation and the internal consumption is 45 MW.

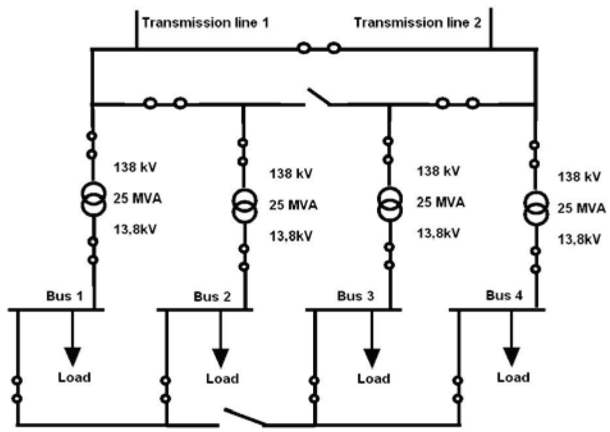

Figure 1 – Electric System of REGAP refinery.

The refinery is controlled and operated by one DCS which is specific for the petrochemical process. Another DCS is responsible for the control of the electric system. The process controllers are fed by 11 double conversion AC UPS as shown in figure 2, equipped with valve regulated lead acid (VRLA) batteries for this purpose. On the other hand, the DCS dedicated to the electric system is fed by rectifiers equipped with flooded batteries.

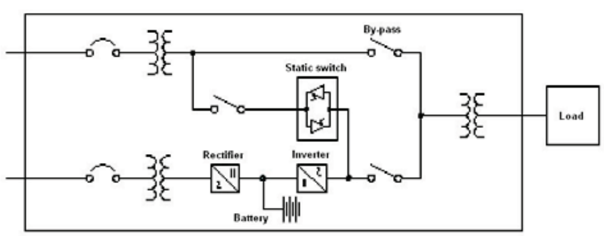

Figure 2 –REGAP AC UPS typical diagram.

The UPS battery has a 100Ah capacity in a set of 32 blocs of 6 elements each. The fluctuation voltage is 436V, the nominal voltage is 384V and the shut down level of the inverter is 308V.

The Electric System Shut Down Event

On November 5th, an initial outage of 6 minutes followed by a recovery of 19 minutes and another outage of 7 minutes in the utilities led to the shut down of five DCS controllers by lack of back up electric energy.

After the restoration of the electric energy, capacity tests were performed on the VRLA batteries of the AC UPS that failed during the mains shut down. The tests were performed with a resistive load equivalent to twice the current at the nominal capacity of the battery. The tests results showed that the batteries had a capacity better than 85% of the nominal capacity, considered enough to feed the critical loads, and superior to the established by IEEE 1188 standard for replacement.

As it was verified that the batteries were fully charged to support the critical loads, there was then a suspicion that the inverter was shut down during the transfer of the load from the rectifier to the battery. Thus, a test circuit as shown in figure 3 was built to simulate the load. The opening instant of the switch was registered by an oscilloscope. All the VRLA batteries that had failed were tested. One VRLA and one flooded battery that had not failed were also tested.

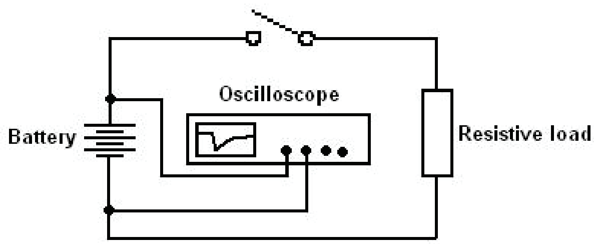

Figure 3 – Load transfer circuit test set.

As shown in figure 4, a sharp voltage dip of 114V with a recovery time of 36 milliseconds can be observed, and the inverter shut down voltage of 308V was reached. The batteries that had failed were tested, and they also exhibited the same behavior, for their terminal voltage transitorily went lower than the inverter shut down voltage.

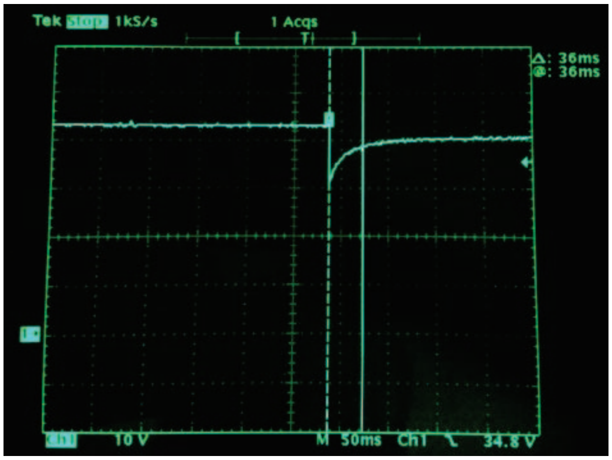

Figure 4 - Oscillogram of one of the batteries that had failed. The vertical grid has the scale of 100V/div and the horizontal 50ms/div.

Figure 5 shows the VRLA battery for which the inverter did not fail. A voltage dip of 58V with a recovery time of 10 milliseconds can be observed.

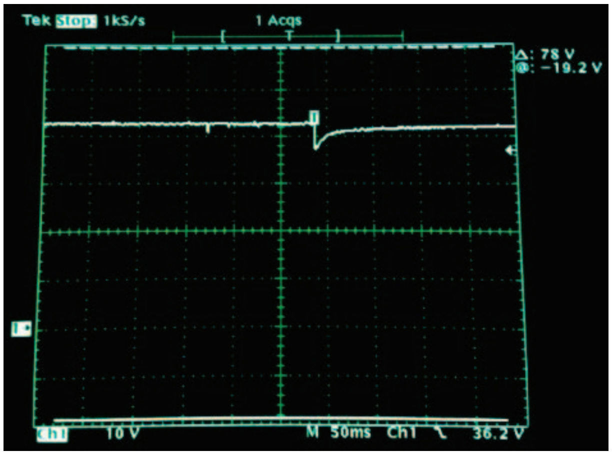

Figure 5 - Oscillogram of one of the batteries that had not failed. The vertical grid has the scale of 100V/div and the horizontal 50ms/div.

Figure 6 presents an oscillogram of a 125 volt flooded battery at the end of its life. A complete voltage dip of 125 volts with a recovery time of 25 microseconds was observed. The test was repeated with the rectifier connected and no voltage dip was observed.

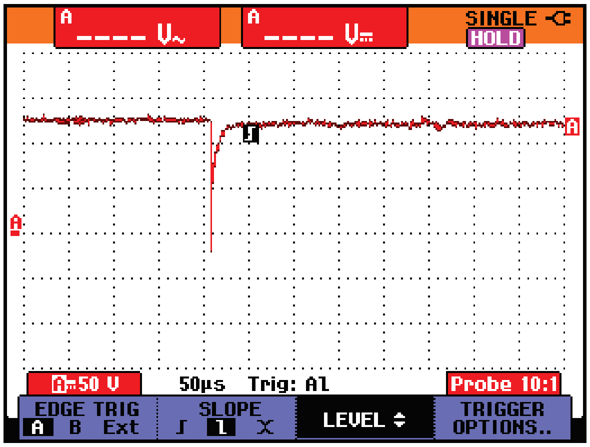

Figure 5 - Oscillogram of a flooded battery at the end of life. The vertical grid has the scale of 50V/div and the horizontal 50µs/div.

According to the tests performed it can be observed that the VRLA battery shows a longer recovery time than the flooded battery. As the recovery time of the flooded batteries are much shorter, the capacitance of the DC link filter was enough to attenuate the voltage dip.

THE *COUP DE FOUET* EFFECT

According to Rocha[1], the dissolution/precipitation model is currently accepted by the majority of researchers in order to describe the reactions that occur on the positive and negative electrodes in lead acid batteries [2,3,4,5]. Essentially, this model proposes that the double sulphate reactions, proposed by Gladstone and Tribe [6], occur by a dissolution/precipitation mechanism. This mechanism assumes Pb^{4+} ions in the PbO_2 matrix, where the interface PbO_2/solution, receives 2 electrons and becomes Pb^{2+} (Figure 7).

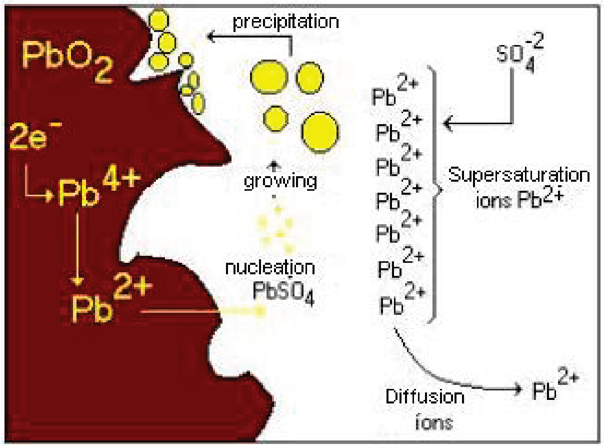

Figure 7 – The Dissolution/precipitation mechanism.

After the transference of the electrons, the Pb^{2+} ions are dissolved in the solution creating a supersaturated state of Pb^{2+} ions. The supersaturated state, according to this theory, is caused by the *coup de fouet* effect, ie, a cathodic peak of potential in the early stages of discharge, allowing for the nucleation of the new phase, the $PbSO_4$, in solution. After the first $PbSO_4$ nucleus appear in the solution, the $PbSO_4$ precipitation over these nucleus would happen in a regular and constant way, in the heart of the saturated sulfuric acid solution of Pb^{2+}. When the lead sulfate reaches its solubility limit, these crystals would precipitate over the PbO_2. A complete review of these processes is available[10] and most recent literature[10, 12] about this subject are periodically published. Figure 7 shows the schematic representation of this mechanism.

The available literature on the *coup de fouet* effect mentions the appearance of a sharp voltage dip of a few millivolts per cell followed by a recovery time in the order of many seconds or even minutes. Researches about this effect[11] show that its extent tends to increase over the battery's life, but the *coup de fouet* effect maintains its initial characteristics of voltage dip and recovery time. Another interesting fact linked to this phenomenon formation is that it occurs at the first few seconds of the initial discharge of the positive electrode, when the sulfate is present under the form of Pb^{2+} ions, forming a supersaturated solution on the surface of the plate, until the formation of micro-crystals of lead sulfate takes place. So, the initial discharge voltage drops by a 20 mV amount or more until sufficient micro crystals have been formed and the supersaturation disappears, restoring the voltage to the specified level.

According to the tests made on the batteries, it could be ascertained that the voltage dip transients of the *coup de fouet* effect are different from the articles (Figures 4, 5 e 6). The tests showed a sharp dip and a recovery time of some tens of milliseconds. It can be observed that even after the first initial discharge, where the supersaturated solution faded away and the micro crystals of lead sulfate were formed, the phenomenon was still present by applying consecutive cycles of discharging. This procedure showed that the chemical inertia was still present also. Another observation is that the voltage recovery time changed with the state of the battery. The voltage dip and recovery time is lower on batteries that have been more charged than on batteries that have been less charged (Figures 4 and 5).

Other set of tests performed for which some elements with high internal resistance were inserted in a new battery, resulted in a significant increase of the *coup de fouet* effect. So the equalization of the elements in the battery is needed to ensure that the battery reaches the end of its life without unwanted surprises.

It was observed that the *coup de fouet* effect becomes worse as the value of the discharge current is increased, leading to the conclusion that a bad battery capacity design may cause unwanted shutdowns of the UPS when the batteries are near the end of their life. The IEEE 485 states that the designer should ensure that the occurrence of a voltage dip during the early stage of a discharge has been taken into account in the manufacturer's published capacity rating factor. The manufacturers however do not make it readily available.

CONCLUSIONS AND RECOMENDATIONS

As a result of this article and the technical literature research, it was observed that:

- The lack of acknowledgement of *coup de fouet* effect may lead to erroneous conclusions that the UPS or inverter has failed when a transfer to the static switch is observed.

- The battery Manufacturers' does not provide the sizing factors to compensate for the *coup de fouet* effect.

- Manufacturers of UPS, rectifiers and inverters do not take into account the compensation for the *coup de fouet* effect in their designs. The DC link filters are sized to minimize the ripple and not to deal with the *coup de fouet* effect, which does not prevent the inverter shutdown. Should the coup de fouet effect be better known, UPS manufacturers' would have a better chance of mitigating its consequences by correctly sizing the DC link filters' capacitors and reactors.

- Flooded lead acid and alkaline batteries are more reliable, and better suited for critical industrial processing equipment.

- Specification and sizing batteries standards do not take into account the influence of *coup de fouet* effect. The IEEE 485 only mentions the existence of the effect: "Batteries experience a voltage dip during the early stage of discharge, following which the voltage shows some recovery."

Recommendations and proposals for future work:

- Including the verification of the *coup de fouet* effect in maintenance procedures.

- Including more rigorous technical requirements on lead-acid batteries acquisition procedures.

- Research to establish a relationship between the coup de fouet effect and the variation of battery capacity and its life.

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