High Level Integration of Power Electronic Controls & Smart Algorithms to Upgrade DC Furnace Rectifiers

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DC EAF (Direct Current Electric Arc Furnaces) have a higher complexity when compared to AC EAFs. The power rectifier and other electronic equipment requires more maintenance and specialized skills from the plant personnel. The new DigiFCR® X4 control platform is used to fully control the Power Converter of a DC EAF, solving the obsolescence problems while eliminating downtime and high maintenance costs caused by outdated equipment. Incorporating smart products on Firing Circuit Replacements it also expands the capability to monitor key performance indicators towards Industry 4.0. DigiFCR® X4 native technology works with DigitARC PX3 electrode regulator to stabilize the arc and work more efficiently. Furthermore, it integrates intelligence tools to get the most of your existing hardware by using real-time data to analyze, learn and predict the power converter performance, properly aligning your technology on the road to digitalization.

KEYWORDS: HIGH LEVEL OF INTEGRATION – DC ELECTRIC ARC FURNANCE – EAF – DIAGNOSTICS – INFORMATION MANAGEMENT.

INTRODUCTION

The rectifier and its current control are the heart of the DC electric arc furnace. Some advantages of a DC EAFs when compared to its AC counterpart, is that the unbalance between phases is minimum and the flicker is reduced. Furthermore, the regulator´s control is easier because there is only one electrode. Nonetheless, the rectifier contains a massive number of semiconductors working in a coordinated way, converting from alternating current to direct current, and allowing the electrical energy flow in a controlled way into the furnace. The semiconductors are based as SCR (Silicon Controlled Rectifiers) also known as thyristors. These SCRs are controlled either by a computer or by an analog system, which regulates the current flowing through the rectifier.

The current control is done by a special current control regulator that is designed to keep the current as close to the reference as possible. If the control system block diagram and transfer function of the furnace is analyzed, we can find the chaotic changes in the system in every moment, and this is caused because we cannot control the scrap movement or how the arc is moving inside the furnace. If the current control is not accurate, the furnace regulator will have a difficult time stabilizing the voltage. Flickering or power dip problems may appear, causing the system not to achieve the electrical energy quality goals required by the regulations stated by the utility company.

In addition, maintaining and troubleshooting a massive rectifier, such as the one used in DC EAFs require specialized skills and nowadays it is more complicated to find individuals with such expertise. The high costs associated with downtime in the meltshop and the inherent impact on production make it imperative to have accurate information to anticipate the problems, and in case of failure, solve them as fast as possible. Therefore, data acquisition is very important and displaying the information in an organized way to the maintenance team so it is understandable and intuitive gives them a valuable advantage to restart production as soon as possible.

ANALYSIS

GOALS DEFINITION AND METHODOLOGY

The figure 1 shows a typical layout of a DC EAF:

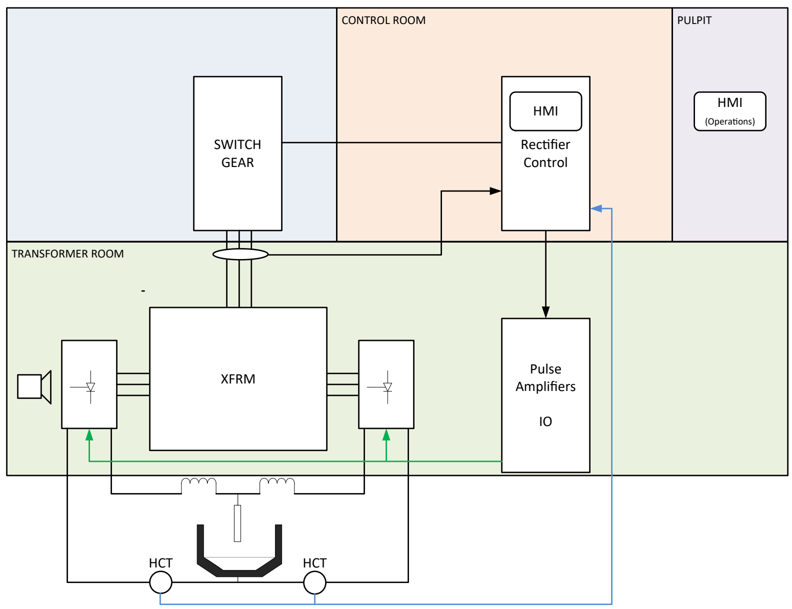

Fig. 1 – Typical layout of a DC EAF

Normally, there is a control room where the main control of the rectifier cabinet is installed. In the transformer room there are cabinets that contain pulse amplifiers and/or I/O. This depends on every specific solution. Also, there is a small HMI for the maintenance of the Rectifier System. Regardless of the reliability of the system, there is few information in the rest of the locations where there is equipment installed.

The main objective is getting an outstanding operation, where the current is as stable as possible, to meet the power quality requirements and keep the stability factor as low as possible with the understanding that even though the stability factor depends on a lot of things, keeping the current stable helps. Another crucial factor to have a reliable operation is protecting the equipment, considering that such protections must act extremely fast, preferably using the same control of the rectifier, and maintaining operative continuity. Occasionally, the system will need to be troubleshooted, either because of any part damage, or because of any permissive missing. That said, it is essential to give the maintenance team the information to anticipate problems and troubleshoot the equipment when needed.

Different methodologies were used to define the appropriate combination of features for the system design.

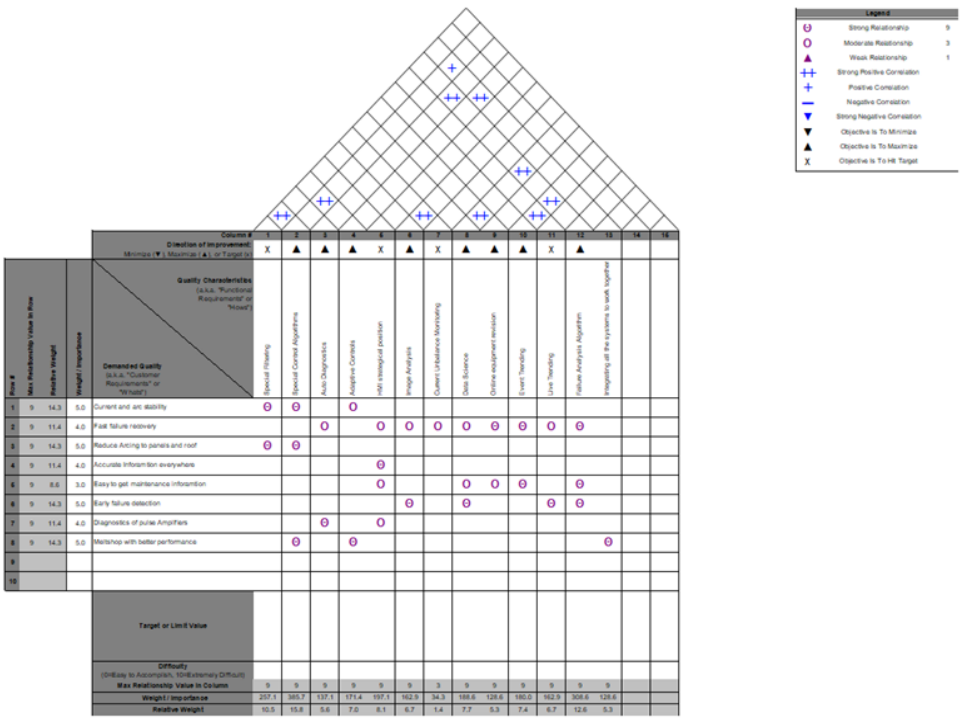

Fig. 2 – QFD Diagram

1. Rectifier control should be steady with minimum deviation especially in the bore in stage of the heat. To accomplish this, special algorithms should be implemented.
2. Integrate the automation of the major meltshops systems to work together in a coordinated way. For example, work together with the Furnace Regulator and the Static Var Compensator together.
3. Protect the equipment. The main goal is to implement early detection of faults. This can be done by monitoring the rectifiers wear and using special algorithms that detect failure before something catastrophic happens.
4. Produce right and accurate information that can assess operational and maintenance risk of the equipment. This information should be given in an intuitive way for the maintenance team.

THE PROPOSED SCHEME

To achieve the goals proposed in the last section, the systems need to be designed in the proper way. The next paragraphs show the proposed scheme in hardware, software, and information management of the DC electric arc furnace control.

1. Hardware

Figure 3 shows a proposed layout. The DC EAF electric system is contained in a control room where the main control of the furnace equipment is installed. The transformer room includes the transformer(s) and power rectifiers. Regardless of whether this room contains the most exposed equipment, no one is authorized to enter unless the system is deenergized. There is another room where the switch gear is placed and lastly another room where the reactors are contained.

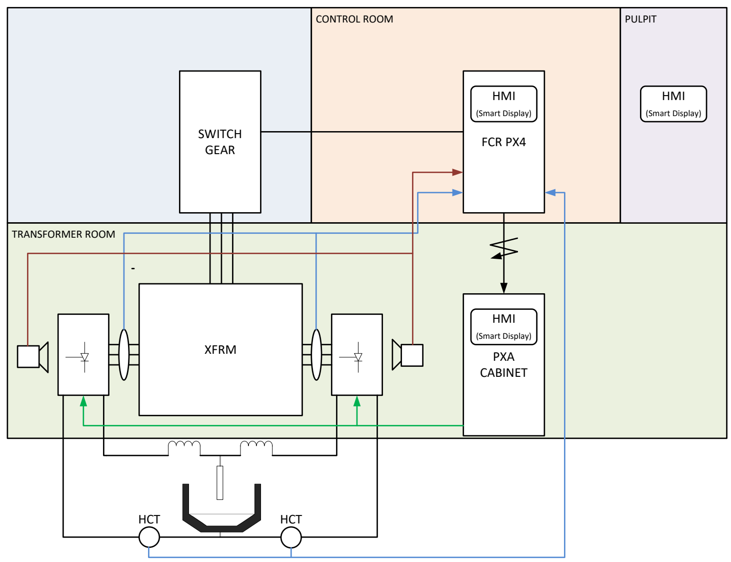

Fig. 3 – Proposed layout of an DC EAF

In the proposed scheme, the control cabinet is installed in the control room and the pulse amplifiers are installed in the transformer room. In both rooms, it is very important to have all the maintenance information and the possibility to command the rectifier's features locally.

The hardware is based on an Ultra High-Performance Controller with hardware dedicated to Control Large Power Electronic Applications in the Steel Industry, called PXC. The PXC receives all the feedback from the rectifier and generates the triggering signals for the SCRs. A control single line diagram of the system is shown in Figure 4.

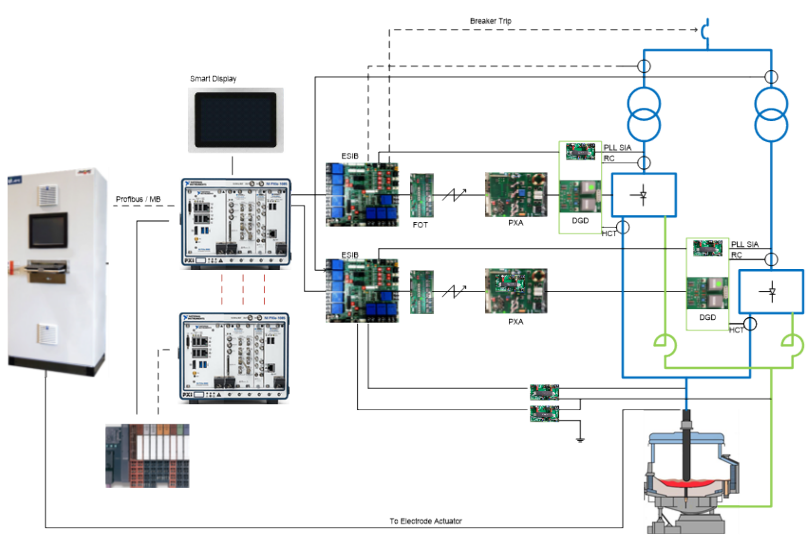

Fig. 4 – Control Single Line Diagram

The PXC receives all the control analog signals through FPGAs (Field – Programmable Gate Arrays). The processor computes all the signals and regulates the current, generating the triggering signals for the SCRs. The triggering signals for the SCRs are generated by the PXC and converted to a fiber optic signal in the FOT (Fiber Optic Transmitter) board. The optic signal will go directly to the PXA, which is the pulse amplifier. The pulse amplifier has auto diagnosis capabilities that will be discussed later. The PXA will generate a powerful pulse that will be received by the DGD boards, which contain the pulse transformers that will get the signal into the SCR.

a. PXC Controller

The PXC controller uses a real-time PCI Express Gen 3 computer which is supported by FPGAs of the latest technology. The amount of FGPA needed depends directly on the application. In the case of a DC EAF, it depends on the number of power rectifiers in the system. The PXC is installed in the control cabinet located in the control room. The FGPAs receive the analog signals that are attenuated in a special group of boards. These boards transform the signals from a power signal to a +/-20ma signal, and an interphase board puts together all the analog signals and take them to the FGPA.

Fig. 5 – PXC Controller

b. PXA pulse amplifiers

The triggering signals are transformed from electrical to an optical signal in the FOT (Fiber Optic Transmitter) board. The PXA pulse amplifier receives a redundant hard clad silica fiber optic signal, that triggers a pulse for the upper leg and lower leg of each phase of the power rectifier. Up to 16 pulse transformers with their SCR can be connected to each firing channel, providing a gating burst up to 16kHz.

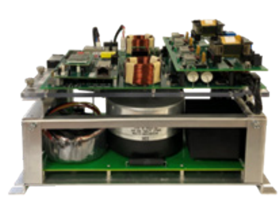

Fig. 6 – PXA pulse amplifiers

The PXA Pulse amplifier has auto diagnostic capability. It is permanently monitoring its multiple power supplies. In case something fails it will send the information to the PXC controller.

AMI

c. Current Monitoring

The current flowing through the rectifier is monitored in two different parts, in the DC side and AC side. In the DC side, HCTs (Hall Effect Current Transformers) are used, mounted in the DC bus. In the AC side, the current is measured either by CTs (Current Transformer) or Rogowski Coils. If the current is measured using Rogowski Coils, the integration of the di/dt is done by software.

The DC current is compared to the AC current on each power rectifier. Comparing the current gives the opportunity to detect a power rectifier failure in a initial stage before it increases the risk into a larger damage. Also, the current in between power rectifiers is compared to detect anomalies in the operation.

In some cases, the current sensors are only on the AC side of the rectifier, mainly CTs, if this is used to regulate and there is no DC current sensor, the protection scheme may change, and will be able only to detect overcurrent, but not a differential protection, due to the lack of instrumentation.

d. Unbalance Detection

The system counts with an optional current measurement of each SCR current. This is done by Rogowski Coils measuring the current in each SCR. This Rogowski coils can be installed either permanently or temporally in separate locations. The system measures the current and calculates the unbalance between SCRs, alarming every time the signal exceeds the threshold set by the commissioning team.

e. Infrared Cameras

Infrared cameras and image analysis are used to measure the temperature in the power rectifiers. Measuring the temperature provides valuable information about the wear in the cooling water pipes of the rectifier, non-conducting SCRs, possible current unbalances, and other issues.

Depending on the transformer room layout, one or two camaras can be installed per power rectifier. The control system analyzes the thermal behavior and, in case of anomalies, alarms the operator so he can take the best decision depending on the situation.

f. Maintenance HMI

The system includes multiple HMI screens for maintenance and operation in different locations. Some of the prefered locations are:

- Pulpit
- Main control room
- PXA cabinets

These HMI screens are for information at each point where maintenance jobs may be performed. The HMI not only shows accurate information to the plant personnel, but also gives the possibility of operating the equipment in maintenance mode.

2. Control Philosophy

There are three main diverse ways to operate the rectifier:

- Operation
- Commissioning
- Maintenance

In this section, only operation mode will be discussed, leaving the other two for the Maintenance tool section. In order to respond to a constantly changing environment, the control system philosophy is designed as a single current regulator with a push pull multi rectifier configuration to balance the current. Such single current regulator has been proven to be more reliable and stable in the above-mentioned conditions. In some specific cases, two or more current regulators may be used.

The current regulator is responsible for regulating the average current of each power rectifier needed by the process, reacting fast to changes, using a special algorithm to keep the current deviation as low as possible. These algorithms consist of a special regulator with specific characteristics in the transfer function, supported by special filters that help to stabilize the regulator when the scrap is moving and reacting inside the furnace. These features help the furnace regulator to have a steadier control of the current helping the furnace regulator to have a better operation.

The push pull regulator keeps the current balanced between rectifiers, comparing the current of each one with the average current and giving an offset to the firing angle of each rectifier. In other words, the current regulator will take care of getting the current used by the process and the push pull balance regulator will give a small offset to the firing angles of each power rectifier to ensure identical current levels across all rectifiers.

The control also contains a smart algorithm that prevents the voltage from rising above a desired limit, reducing the risk of arcing to the panels or the roof of the furnace. This smart algorithm adjusts the set points and gains depending on the stage of the heat.

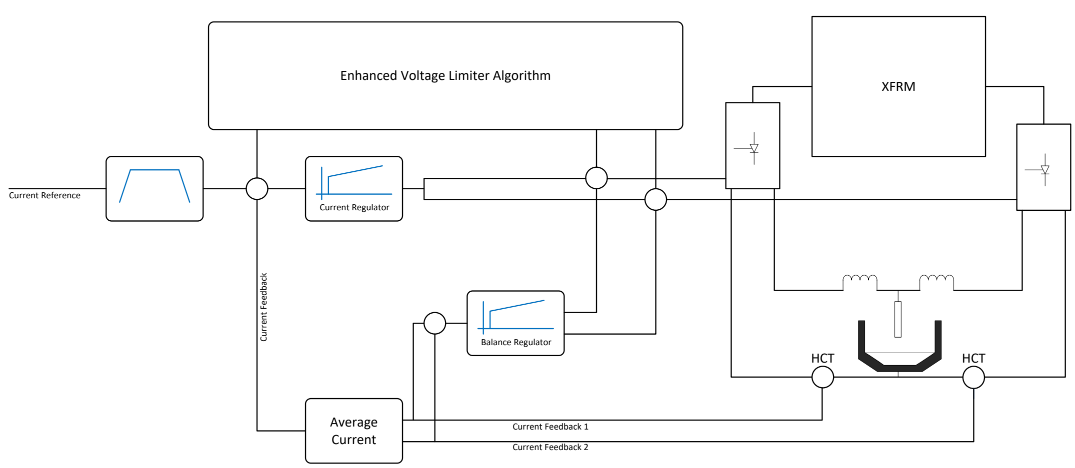

Fig. 7 – Control Block Diagram

The rectifier is also protected by the software implemented on its control. A protection means something that cannot wait for the operator to act, and the system trips the furnace. The control system contains special algorithms that protect the transformer and rectifier in every moment. Some of the protections are related to the current and voltage feedbacks in the system:

- Over Current DC/AC. Detects a large amount of current that goes above the protection threshold.
- PLL (Phase Lock Loop) regulator is lost.
- AC>DC. The AC current feedback is compared to the DC current. If the AC goes higher than DC the system will trip. Most of the time this protection reacts faster than the over current.
- Current unbalance between rectifiers.

The system also contains other protections that take decisions in case of an event but do not trip the furnace. For example, if a fuse is blown, the current reference will be reduced to finish the heat but with less power available. The same happens if the infrared cameras detect that the power rectifiers are heating up, the system may take the decision to reduce the current set point to finish the heat before it trips. Any of these conditions will alarm the operator. There are other events that will alarm the operator, but the system will not act.

3. Working together with the regulator and SVC.

The control system for the DC EAF, is prepared to work with any brand of regulator, but it has a native integration to work with the DigitARC PX3 and the Digi SVC. The system shares information with the regulator and the SVC and the PX3. The PX3 knows what it is doing and will adjust set points in case is needed, and the SVC is informed of the actions taken by the EAF, preparing itself to react depending on the kind of action taken by the system.

4. Information Management

Some parts of the systems can auto-diagnose themselves and send the information to the main control. This opens the possibility to detect wear in some of the main components of the rectifier control and inform the plant personnel.

Starting from the PXA pulse amplifier. The amplifier monitors its power supplies continuously and every predetermined time checks the pulse waveform of one pulse. In the case of the power supplies, if one of them fails the system will trip immediately, because this can lead to catastrophic damage. In the case of the pulse wave form analysis, the information is sent to the main control system PXC computer where it is analyzed. If the pulse changes its wave form, it will send an alarm to the operator. Since it is possible to operate with this issue, at least for a brief period, the operator will take the decision of stopping or wait until a small outage and ask the maintenance personnel for the revision of the pulse amplifier.

The control analyzes the images gathered from the infrared cameras inside the transformer room and is monitoring the temperature of the rectifier. The information is used to detect problems like unbalance, water flow issues and faulty SCRs. This information may display an alarm to the operator.

The unbalance detection is enhanced by installing Rogowski coils for each SCR. The Rogowski Coil signal is integrated by software. The current of each SCRs is measured and compared to the average current of the others.

All the protections and alarms are analyzed and recreated on the PXC computer. The difference between them is that the protections will trip the system immediately, while the alarms will display the information to the operator so he can take decisions on how to proceed. The system summarizes and gives essential and accurate information about the alarms to the operator and the maintenance team. The information is shown in different HMI screens that are installed strategically in the places where most of the maintenance jobs should be done, for example, in the rectifier room, in the control room, pulpit and others. The reason for this is to avoid misunderstanding in the radio communications between maintenance and operation personnel.

The information gathered in the PXC can be recorded in a database and transferred to the cloud, where it is analyzed with statistical algorithms to get valuable information for maintenance and troubleshooting.

The Figure 8 is a representation of what has been said in this section, the red lines show the flow of information to the PXC controller.

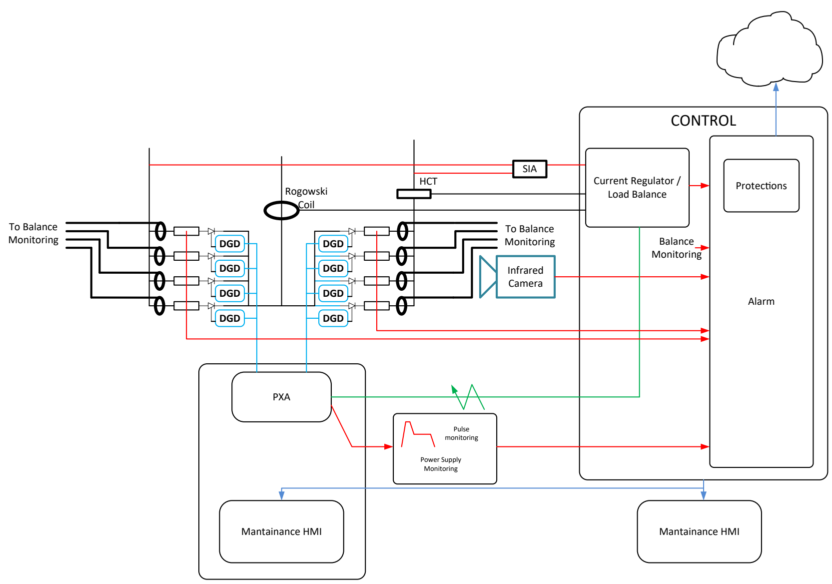

Fig. 8 – System Flow Information Diagram

5. Maintenance tools

The new system counts with different software tools for trouble shooting and maintenance tools. These tools are designed to give pertinent information to the personnel that will intervene with the equipment. Some of these tools are the Smart Display (HMI), Smart tool, and event recorder.

When talking about maintenance tools for the DC EAF, the Smart Display is the front line. The Smart Display is an HMI that should be installed in every place where there is rectifier hardware. The smart display can show the operative parameters, trend, and alarms/faults. The analysis of the situation done in the PXC is displayed in the controller, showing accurate instructions to proceed in case of an event.

The smart display also operates the rectifier in the Commissioning and Maintenance Mode:

a. Commissioning Mode. - This mode gives full control to the Smart Tool and ignores operators' set points and commands. This is used for commissioning purposes and in some cases, to do some checkups during maintenance operations.
b. Maintenance Mode.- In maintenance mode the systems locks the switch gear (The system will send a permanent trip to the switch gear, but is imperative to do the proper lock out, tag out, try out of it) and allows the maintenance personnel to run special test that will help them to review the situation of the rectifier, such as firing test, where they may check the quality of pulses on the pulse amplifier modules, and others.

The Smart Tool is a commissioning tool. In the Smart Tool it is possible to adjust gains and scaling of signals, do step test to see how the regulators are working, and activate or deactivate protections. The Smart Tool is always available and may be used in normal operation.

In commissioning mode, the smart tool will allow the system to enter in a test mode, steps might be commanded review a specific behavior of the rectifier during a warm commissioning period. Also, allows the user to adjust parameters and gains during normal operation.

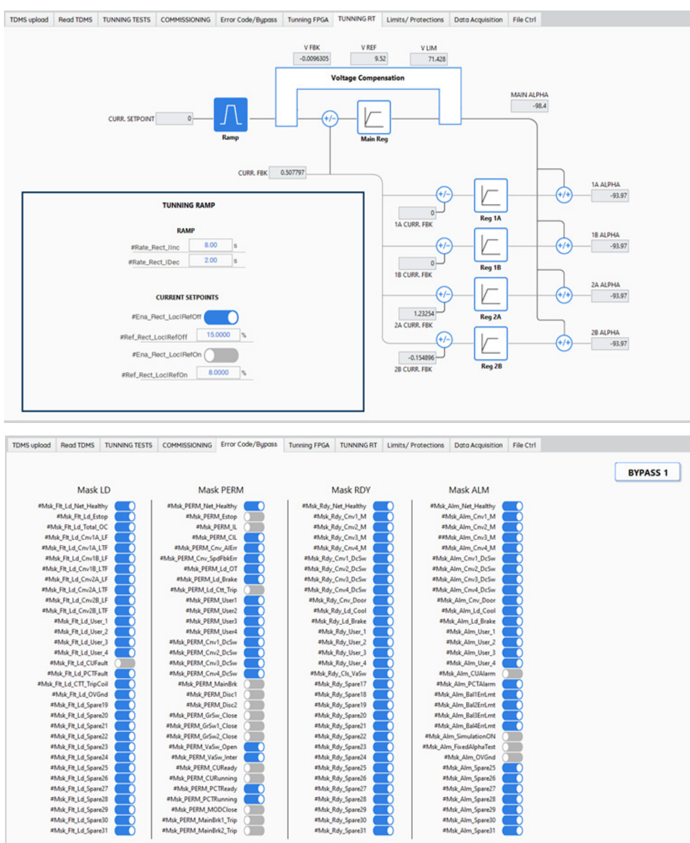

Fig. 9 – Smart Tool

The event recorder records a high-speed trend (277us sampling) of a specific event. An event is defined as a fault that needs to shut down the rectifier immediately, a specific alarm, or predetermined signal that gets to certain level specified during the commissioning, for example a change in the current refence, or a specific current deviation. The Figure 10 shows an example of the high-speed trend.

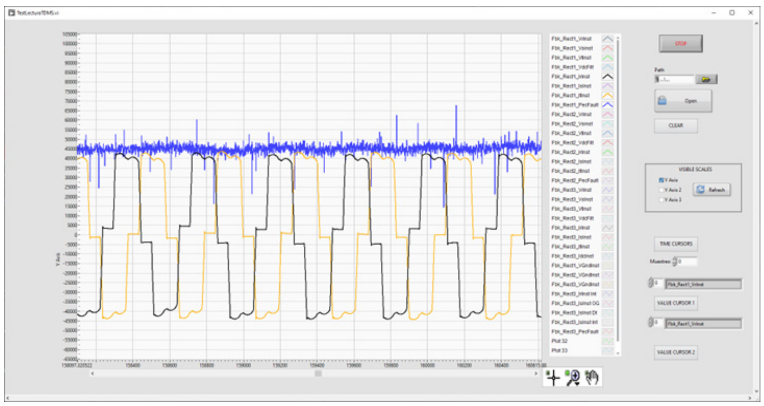

Fig. 10 – High Speed Trend Example

The information recorded helps to understand what was happening in the rectifier moments before an event and adds immense value for diagnostic purposes.

RESULTS

Some of the results of implementing a high level integration are the following:

- Great level of information to tune up the rectifier current algorithm to maintain the deviation as low as possible, getting a more efficient operation of the regulator.
- Superior fault diagnosis that leads to a final solution of the issues going on in the furnace.
- Information that leads to preventive and predictive maintenance of the furnace. The information given to the operator leads to take decisions on when to stop, and how to stop the furnace, interfering less with the operation and reduce sudden downtime.

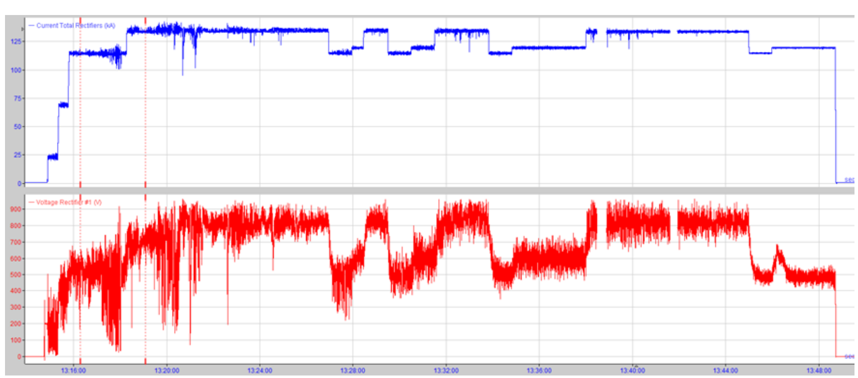

Fig. 11 – DC EAF Current Regulation Trend

CONCLUSIONS

Similar to any team integrated by persons (examples: sports, business or others), highly integrated productive facility also makes the separate subsystems work together in between and with the plant personnel to enhance the operation and keep a high availability of the equipment. The subsystems should work together and should give the information to the personnel to take a higher-level type of decisions.

In a melt shop facility, and in this specific case talking about a DC EAF, integrating the rectifier with the arc regulator and the Static Var Compensator control, allowed to prepare the incoming power line from the grid for some of the transients caused by the furnace operation. For example, disconnecting and connecting the arc, energizing the transformer and others type of events. The system allows to feedforward the Static Var Compensator with information that will allow to react smoother against the chaotic behavior of the furnace.

Effective control systems are not solely characterized by their ability to operate smoothly and deliver superior quality to the process and final product, they are also supposed to anticipate, predict, and mitigate the inevitable failures or mistakes caused by electronic equipment, environmental, rare operations, or humans' factors. They should also provide accurate information in a timely and appropriate manner to the users, thus having a high-level integration system that displays the most relevant information gives less room for interpretation for the operators giving them better tools not only to solve problems but also to have a steady operation.

The integration of the system was tailor designed to give the information they need to each part of the team who is going to maintain and intervene the equipment. The results are faster and accurate diagnostics, a quicker recovery, which it was achieved because there where accurate instructions to the technicians. The integrated system of the DC EAF offers significant benefits to the maintenance team by streamlining communication and providing uniform information gathered from various parts of the plant. This shared information ensures that all users have access to identical data, thus reducing troubleshooting time and serving as a valuable asset to the melt shop's maintenance team.