ISEC – SMART ELECTRODE CONTROL*

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Abstract

Electrode controllers have a significant influence on the productivity of electric arc furnaces. Melting time, electrode, refractory, energy consumption, stress on resources (e.g. electrode arms, high current lines, etc.) are all influenced by electrode control. Constant power input at defined working points, short tap-to-tap times and less electrode and refractory material consumption are the most important requirements from a furnace operations perspective. The ISEC electrode controller was developed based on such modern furnace operation requirements for electric arc and ladle furnaces in the iron and steel making industry (EAF, LF, VHD/VAD).

Keywords: Electrode control system; EAF monitoring system; APLAN; INTECO.

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** Technical contribution to the 54º Seminário de Aciaria, Fundição e Metalurgia de Não-Ferrosos, part of the ABM Week 9th edition, September 9th-11th, 2025, São Paulo, SP, Brazil.*

1 INTRODUCTION

An electrode regulation system based on Digital Electrode Control (DDC) is expected to offer the optimum solution for electric arc and ladle furnaces in the iron and steel making industry (EAF, LF, VHD/VAD).

The digital electrode controller regulates the electrical power supply for electric arc and ladle furnaces. It ensures that the required amount of energy is supplied in the shortest amount of time to the metal being heated.

The main advantages of the electrode regulation system are:

- Maximum power range by adapting the controller to the heating conditions.
- Long exploitation of the transformer's highest power setting.
- A connected controller alters the current, and therefore the arc length, based on the heating condition without reducing the voltage level.
- Easy and clear parameter adjustments.
- Quick and easy diagnostics in addition to relevant information.

The main characteristics of the electrode regulation system are:

- Short cycle time.
- Pre-set operating points using a current voltage curve.
- Adjustable control parameters.
- Marginal conditions (dependent on the operating point).
- Overcurrent recognition and regulation.
- Deadbands for calm furnace operation.
- Limitation of the electrode speed.
- Level change value separated for raising and lowering.
- Fast lowering after switching on the furnace.
- High control dynamic.
- Integrated test programs recognize and correct, if possible, occurred troubles.

2 DEVELOPMENT

The ISEC smart electrode control was designed as the next step in bringing electric arc furnaces nearer to a smart processing methodology.

ISEC dynamically controls the electrode movement at an optimum working point to efficiently convert the electrical energy into heat.

ISEC was developed considering the modern operation requirements for electric arc and ladle furnaces in the iron and steel making industry (EAF, LF, VHD/VAD). Additionally, ISEC can control submerged arc operation, broadening the range of application to all types of electric furnaces that process non-ferrous metals, ferro-alloys and slag heating.

ISEC is a new digital electrode control system that utilizes a state-of-the-art embedded controller, enabling real-time sampling and precise computations of all electric values. A modern web-based visualization system is integrated for flexible operation and fast diagnostics.

The smart electrode control functions not only as a controller, but also a database server, enabling full integration into smart factory – Industry 4.0 – environments.

2.1 The ISEC System.

The ISEC electrode controller consists of two components in the basic package.

- ISEC main box

- UI-box

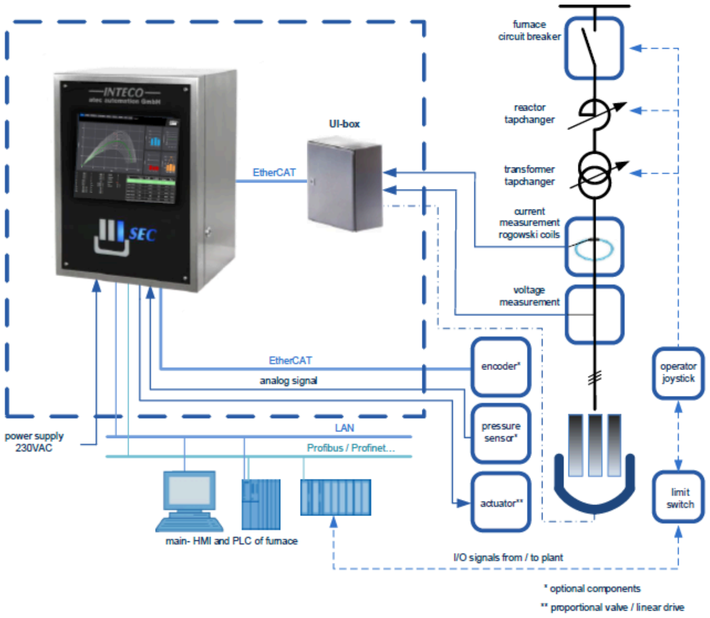


Figure 1. System overview ISEC basic equipment.

2.1.1 ISEC main box

The main box consists of a power supply and a controller with I/O and interface modules.

2.1.2 UI-box

The UI-box measures currents, primary or secondary (secondary being standard), via Rogowski coils or current transformers on the furnace transformer. The measurement module within the UI-box performs the signal processing.

Primary or secondary voltages (secondary being standard) are measured by voltage transformers integrated in the UI-Box. The resulting transformed voltage signals are connected to the measurement module. Additionally, safety devices and surge arresters are integrated in the UI-Box.

2.2 Technical data

item	data
ISEC cabinet	stainless steel, 480 x 690 x 330mm (wxhxd) approx. 40kg
UI-box	stainless steel, 500 x 500 x 300mm (wxhxd) approx. 20kg
power supply	230 VAC (1A)
monitor	multi-touch, 17”
main cycle time	<10ms
current measurement	Rogowski coils or current transformer (primary or secondary)
voltage measurement	protected voltage transformer
control output	-10V…..+10V standard, different configuration e.g. +/- 300mA or +/- 200 mA are available on request
ambient temperature	-10…..+45°C
relative humidity	5…..90%

Figure 2. Technical data ISEC electrode control.

2.3 Measurement

2.3.1 Acquisition

The measurement is taken on the secondary side of the furnace transformer – primary side measurement is also possible.

The following signals are measured by the UI-box:

- electrode voltage – furnace ground for each electrode
- current for each electrode

2.3.2 Signal processing

The data acquisition rate is 2.5 kHz. The following values are evaluated for the control algorithms:

- Electrode currents I_{1RMS}, $I_{2RMS,}$ I_{3RMS}
- Line voltages (Line-Furnace ground) U_{1RMS}, U_{2RMS}, U_{3RMS}
- Line to line voltages U_{12RMS}, U_{23RMS}, U_{31RMS}
- Total power S_1, S_2, S_3, S_{tot}
- Active power P_1, P_2, P_3, P_{tot}
- Apparent power Q_1, Q_2, Q_3, Q_{tot}
- Power factor PF_1, PF_2, PF_3, PF_{tot}
- Frequency f
- FFT and THD analysis up to 20th harmonic for voltage and current

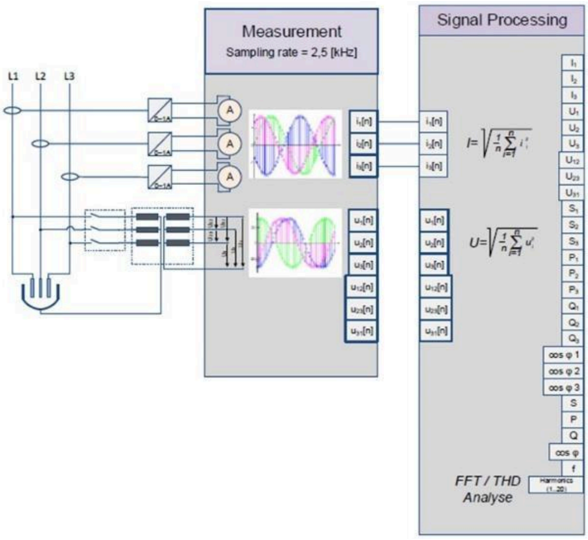


Figure 3. Measurement and signal processing.

2.4 Controller

The main task for the electrode controller is to provide constant melting processes at defined working points. The working point is defined by secondary voltages (trafo tap) and arc lengths, depending on the position of the electrodes and the material in the furnace (e.g. scrap, liquid bath).

The ISEC control algorithm is based on an impedance controller with current-guided set value. The main advantage of impedance control is that, unlike current, imprudence is not interlinked within the three-phase system. Hence, independent control for each electrode is possible, allowing the achievement of a constant current profile for a given set point for each electrode.

2.4.1 Circuit diagram and working point

Working points for the furnace are defined by set values. The circuit diagram (power diagram, current diagram) is dependent on the furnace’s electrical parameters. This diagram allows for easy determination and observation of working points.

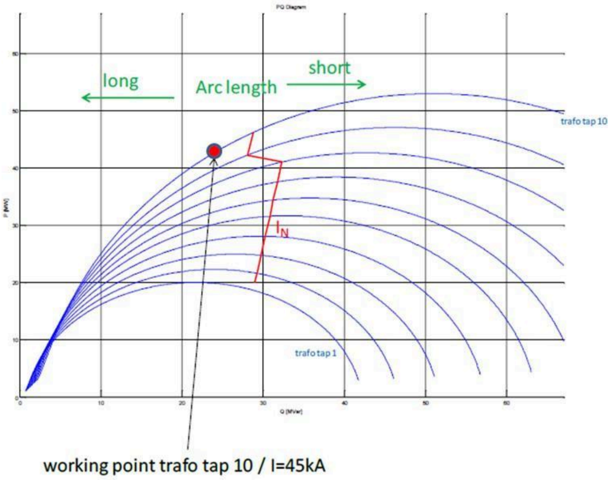


Figure 4. Power diagram - PQ diagram with working point transformer tap 10 / Setpoint **I**=45Ka.

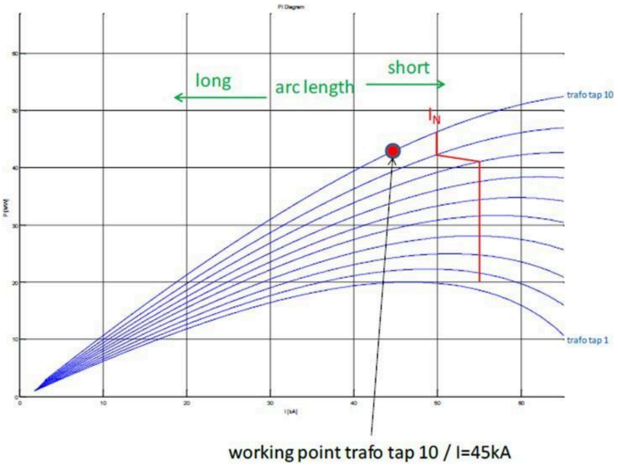


Figure 5. Current diagram - PI diagram with working point transformer tap 10 / setpoint **I**=45kA.

2.4.2 Setpoint – Workingpoint

The ISEC electrode control system provides different ways of setting the working point.

Local set point values on the controller are editable via the:

- visualization software
- communication interface to the furnace PLC
- higher level system

The ‘Melting mode’ parameter allows switching between using single values for current, impedance or arc length, and controlling furnace operation via an operating profile as set point source. Different working points for a single melting process can be defined in an operating profile. Up to 100 operating profiles can be defined (see Figure 6 and Figure 7).

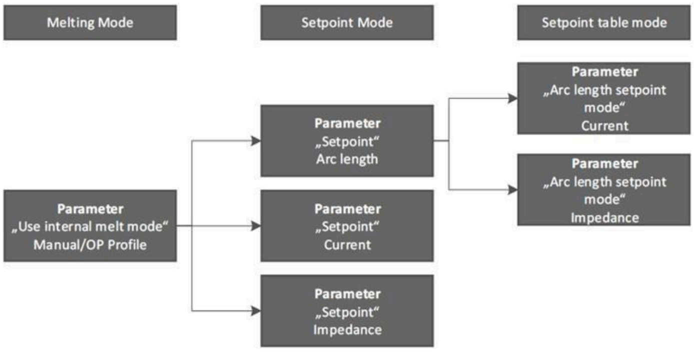


Figure 6. Melting Mode and Setpoint Mode with parameter.

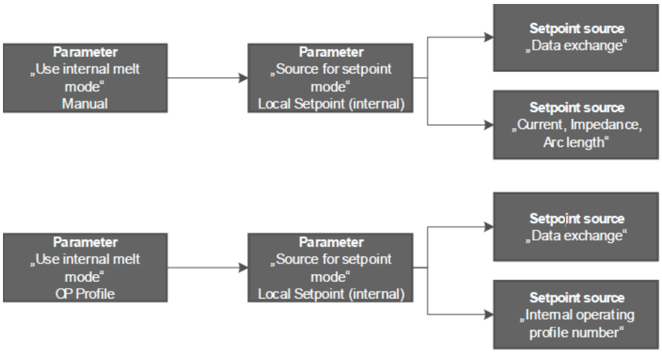


Figure 7. Setpoint source data exchange from furnace PLC or local parameter.

2.4.3 PID control

The ISEC electrode control is based on a standard PID controller that can be adapted according to the requirements of a melting process.

The actual impedance is determined through the measurement of the voltage and current values. The PID controller generates a control signal for the movement of the electrode arms, based on the difference between the actual value and the set point. The I- and D- part of the controller can be disabled, with the P- part remaining perpetually active.

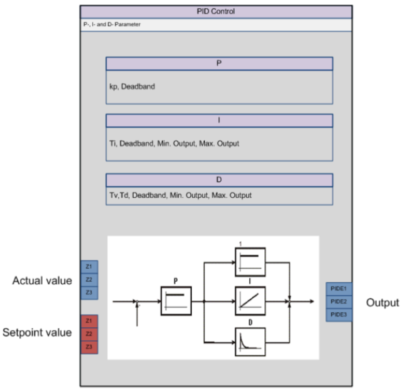


Figure 8. PID Controller.

2.4.3.1 Advanced control

Through dynamic adaptation of the parameter, depending on the different phases of the furnace operation, the system can react to actual conditions during the melting process. Results from the current and voltage signal FFT analysis or the standard deviation are appropriate indicators of melting process progress.

2.4.3.1.1 Adaptive deadband

The dead band can be set depending on the process state. Unstable phases during scrap melting can utilize a wider deadband compared to a liquid bath phase.

2.4.3.1.2 Adaptive gain

Similar to the adaptive deadband, the gain can also be adapted to the actual melting process situation. During the bore down phase, it is possible to reduce the gain to avoid pumping movements of the electrode arms. For the liquid phase, the gain is increased for an appropriate reaction to small control deviations.

2.5 Overcurrent protection

Scrap fall can lead to massive overcurrent events. To reduce the impact on electric equipment, it is necessary to swiftly alleviate overcurrent events. The reaction time of the standard operating mode's impedance controller would not be sufficient. Therefore, an additional overcurrent protection is implemented.

The overcurrent protection works in two steps utilizing two different current limits. Reaching the first current limit the electrode with the overcurrent event will be moved up with an additional control output till the actual current value falls below the limit. Should the second current limit be reached, all electrodes are rapidly elevated with an additional control output until the current value falls below the predefined limits.

2.6 Break detection

Without an additional break detection, an electrode's touchdown on non-conductive elements yields an electrode break. To avoid this scenario, the hydraulic pressure within the electrode arm cylinders are monitored. If the pressure falls below a set limit, the electrode arm will be moved upward. An alarm is generated after an adjustable count of consecutive break detection events.

2.7 Visualization

Relevant process information is consolidated on this display, featuring:

- Circle diagram (furnace power diagram) with actual measurement points
- Actual voltages of the electrodes
- Actual currents of the electrodes
- Actual movement of the electrodes
- Actual arc length of the electrodes
- Energy input information to for the actual heat and last preceding five heats

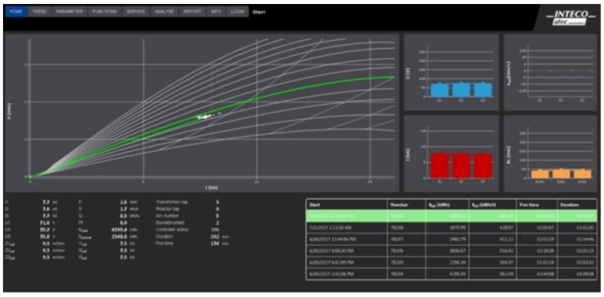
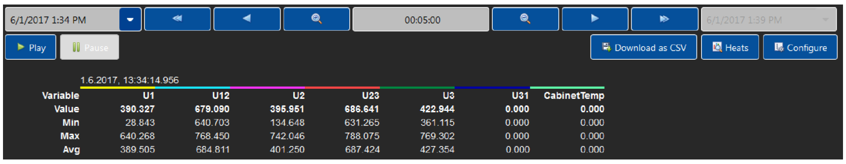


Figure 9. Home screen.

The trend menu provides complete adjustability and configurability for live and historical data trends.

Figure 10. Trend screen.



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Variable	U1	U12	U2	U23	U3	U31	CabinetTemp
Value	**390.327**	**679.090**	**395.951**	**686.641**	**422.944**	**0.000**	**0.000**
Min	28.843	640.703	134.648	631.265	361.115	0.000	0.000
Max	640.268	768.450	742.046	788.075	769.302	0.000	0.000
Avg	389.505	684.811	401.250	687.424	427.354	0.000	0.000

Figure 11. Trend control and variable view.

2.8 Vale Onça Puma Implementation

In April of 2024, a new electrode control system was commissioned for Vale-Onca Puma's ladle furnace station. Alongside the newly implemented "Inteco smart electrode system" (ISEC), an UI-Box for voltage and current measurement was also installed.
The following tasks for the installation and commissioning of the ISEC automation system were carried out:

- ✔ The electric measurement system was checked for correct functionality.
- ✔ The hydraulic system, specifically concerning the electrode arms, was tested by proceeding valve scaling procedure for accurate movement behavior.
- ✔ An open circuit test was carried out to determine the correct voltage conditions of the transformer taps in use.
- ✔ A short-circuit test was carried out for the correct ISEC parameterization of the high current system, enabling accurate calculation of impedance values for current controlling.
- ✔ Heat monitoring was carried out to further evaluate the controller settings and observe overall correct functionality.
- ✔ A PID controller optimization was performed to ensure stable arc conditions and a improved power input throughout different heat periods.

2.8.1 Main data of the VALE power supply

Figure 12 shows the simplified single line diagram of the main power grid to the ladle furnace station. The connection to the public network (point of common coupling) at Onca Puma is supplied by the 230 kV line. A 160 MVA step-down transformer facilitates the electrical power transmission from 230 kV to 34.5 kV of the dirty bus.

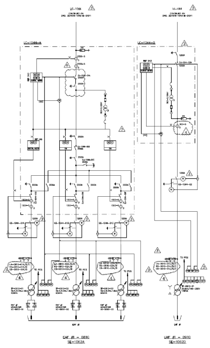
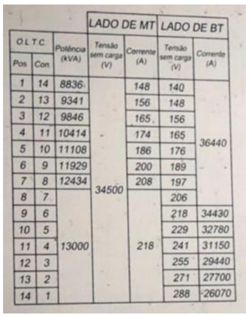


Figure 12. Single line diagram to LF.

From the 34.5 kV busbar to the ladle furnace station, a 13 MVA transformer with star-delta connection is used for power supply.
An extract of the rating plate of the transformer is depicted in Figure 13.



O.L.T.C		Potência (kVA)	LADO DE MT		LADO DE BT	
Pos	Con		Tensão sem carga (V)	Corrente (A)	Tensão sem carga (V)	Corrente (A)
1	14	8836	34500	148	140	36440
2	13	9341		156	148	
3	12	9846		165	156	
4	11	10414		174	165	
5	10	11108		186	176	
6	9	11929		200	189	
7	8	12434		208	197	
8	7	13000		218	206	
9	6				218	34430
10	5				229	32780
11	4				241	31150
12	3				255	29440
13	2				271	27700
14	1				288	26070

Figure 13. Rating plate furnace transformer.

2.8.2 Valve scaling

To ensure correct electrode movement, a valve scaling was recorded to guarantee certain speeds for specific valve openings.

Measurements were taken with a distance laser to determine the electrode speed at different valve openings. Also important was to set the electrode movement to be sensitive at smaller valve openings to prepare for more stable conditions.

The measured values are listed in the following tables.

Table 1. Measured valve parameters of electrode 1, 2 and 3

Electrode 1			Electrode 2			Electrode 3		
Valve scale y [%]	Velocity v [mm/s]	Direction	Valve scale y [%]	Velocity v [mm/s]	Direction	Valve scale y [%]	Velocity v[mm/s]	Direction
-100	-300.00	Down	-100	-300.00	Down	-100	-300.00	Down
-40	-139.47	Down	-40	-146.86	Down	-40	-137.20	Down
-30	-109.30	Down	-30	-108.00	Down	-30	-104.90	Down
-20	-68.67	Down	-20	-70.73	Down	-20	-72.20	Down
-15	-50.80	Down	-15	-51.27	Down	-15	-53.35	Down
-10	-33.13	Down	-10	-33.20	Down	-10	-33.47	Down
-7	-19.63	Down	-7	-21.73	Down	-7	-21.85	Down
-5	-13.40	Down	-5	-14.55	Down	-5	-14.15	Down
-3	-6.00	Down	-3	-7.17	Down	-3	-7.07	Down
-2	-2.33	Down	-2	-3.98	Down	-2	-3.87	Down
2	13.50	Up	2	11.55	Up	2	11.20	Up
3	18.75	Up	3	16.75	Up	3	17.95	Up
5	29.27	Up	5	28.10	Up	5	27.50	Up
7	38.40	Up	7	37.73	Up	7	39.40	Up
10	51.10	Up	10	54.20	Up	10	55.70	Up
15	72.25	Up	15	69.80	Up	15	73.70	Up
20	86.00	Up	20	80.40	Up	20	81.00	Up
30	120.44	Up	30	116.47	Up	30	117.89	Up
40	144.00	Up	40	135.38	Up	40	138.13	Up
100	300.00	Up	100	300.00	Up	100	300.00	Up

The following figures depict the related scaling graphs. It is evident that measurements within the range of slow movement, around the zero point, were executed with greater detail.

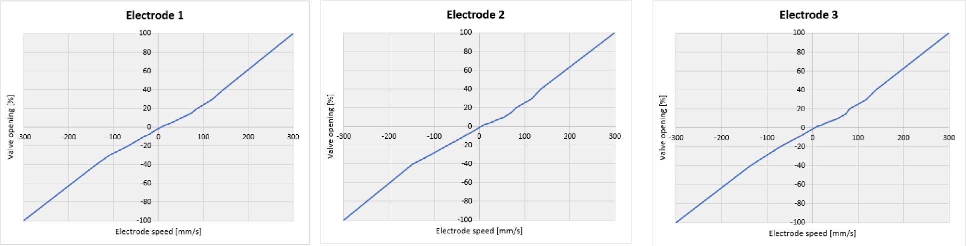


Figure 14. Valve scaling graph of electrodes.

Valve scaling is the process of adjusting the control settings in the automation system, ensuring the valve's proportional response to input signals for precise control of LF parameters, such as electrode positioning, which is necessary for correct impedance controlling.

2.8.3 Short Circuit Test

The short circuit impedances of an electrical arc furnace (EAF) or ladle furnace (LF) determine the electrical behavior of the furnace. Their knowledge is important for power input valuations.

2.8.3.1 Short Circuit Test – Execution

Two-phase short circuit means that only one electrical circuit of the three phases is active, and one electrode is current-less. The remaining two are dipped into the liquid steel bath with supply voltage engaged, consequently carrying equal currents. The current-less electrode should only be raised enough to ensure zero current, as higher positions would excessively change the inductive coupling of the three phases (compared to the desired standard configuration with levelled arms).

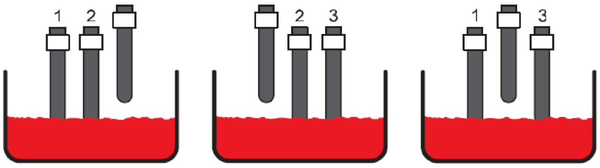


Figure 15. Execution of three 2-phase dip tests.

Measured Values:

- Phase-to-phase voltages U_{ij}
- Line currents I_{ij}
- Active powers P_{ij} (calculated)

The three two-phase dip tests were carried out at the lowest trafo tap. The measured data was used to calculate the resistances and impedances of the secondary side to update the electrical parameters of the high current system in the ISEC.

The electrical parameters were measured by the UI box, recorded by the ISEC and exported thereafter for evaluation.

Presented in the following are the dip test trends of the line currents, phase-to-ground voltages and active powers. Initially, electrodes 1 and 2 were dipped into the melt, followed by electrodes 2 and 3, and finally electrodes 3 and 1.

The values derived from these measurements correspond to those of a comparable LF. Consequently, the ISEC settings were updated and tested based on the newly calculated short circuit values.

Nevetheless, the results of a short-circuit measurement are not trivial and deviations can occur because of influences by unknown electrode lengths and arm positions.

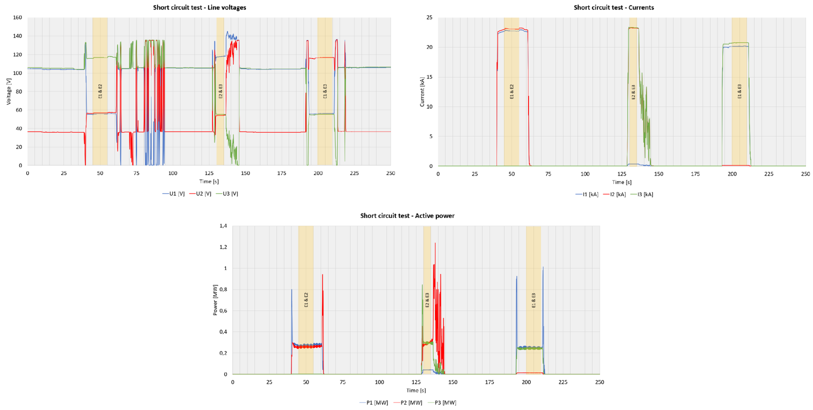


Figure 16. Measured line voltage, currents and active power of short-circuit test.

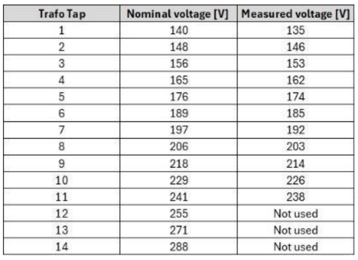
2.8.4 Open circuit test

An open-circuit test is used to check the properties of an electrical system by measurement with no load and to determine the iron losses of an electrical machine.

Furthermore, it can be used to check the ISEC system's voltage measurement and for comparing the measured voltages with the transformer's data sheet specifications. The voltage pickup is performed directly with cables at the high current system, with the three phases measured against the grounding.

For that reason, an open circuit test was performed, and the values listed in the following table were measured and updated in the ISEC electrical parameter settings. The transformer taps from tap 12 upwards are not utilized for operation and their evaluation was not possible given the customer's conditions. However, the measured values meet the expected range.

Table 2. Measured values of the open circuit test



Trafo Tap	Nominal voltage [V]	Measured voltage [V]
1	140	135
2	148	146
3	156	153
4	165	162
5	176	174
6	189	185
7	197	192
8	206	203
9	218	214
10	229	226
11	241	238
12	255	Not used
13	271	Not used
14	288	Not used

2.8.5 PID controller optimization

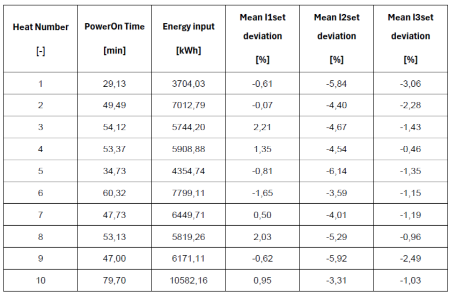
To determine the best-fitting PID settings, an experimental plan was established. The wide range of operations presented difficulties that needed to be managed.

Continuous evaluation of the heats was necessary to declare the different areas of interest relating to the controller parameters. The main criteria for selecting the best possible settings are deviations from the set impedance, which affect the currents and arc lengths. The smaller the deviation is, the more accurate the regulation of the set current, which results in more stable process conditions and better arc stabilities.

In this report, ten heats were additionally analyzed in detail. Every phase was checked in relation to its trend in current, voltage, impedance and electrode movement behavior.

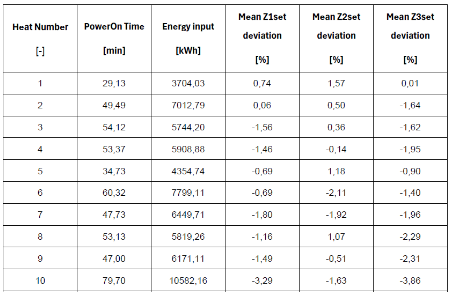
The mean deviations of the current and the impedance from their belonging set values are listed in table 3 and table 4. Additionally, the deviations are plotted in figure 17.

Table 3. Evaluated current deviations



Heat Number [-]	PowerOn Time [min]	Energy input [kWh]	Mean I1set deviation [%]	Mean I2set deviation [%]	Mean I3set deviation [%]
1	29,13	3704,03	-0,61	-5,84	-3,06
2	49,49	7012,79	-0,07	-4,40	-2,28
3	54,12	5744,20	2,21	-4,67	-1,43
4	53,37	5908,88	1,35	-4,54	-0,46
5	34,73	4354,74	-0,81	-6,14	-1,35
6	60,32	7799,11	-1,65	-3,59	-1,15
7	47,73	6449,71	0,50	-4,01	-1,19
8	53,13	5819,26	2,03	-5,29	-0,96
9	47,00	6171,11	-0,62	-5,92	-2,49
10	79,70	10582,16	0,95	-3,31	-1,03

Table 4. Evaluated impedance deviations



Heat Number [-]	PowerOn Time [min]	Energy input [kWh]	Mean Z1set deviation [%]	Mean Z2set deviation [%]	Mean Z3set deviation [%]
1	29,13	3704,03	0,74	1,57	0,01
2	49,49	7012,79	0,06	0,50	-1,64
3	54,12	5744,20	-1,56	0,36	-1,62
4	53,37	5908,88	-1,46	-0,14	-1,95
5	34,73	4354,74	-0,69	1,18	-0,90
6	60,32	7799,11	-0,69	-2,11	-1,40
7	47,73	6449,71	-1,80	-1,92	-1,96
8	53,13	5819,26	-1,16	1,07	-2,29
9	47,00	6171,11	-1,49	-0,51	-2,31
10	79,70	10582,16	-3,29	-1,63	-3,86

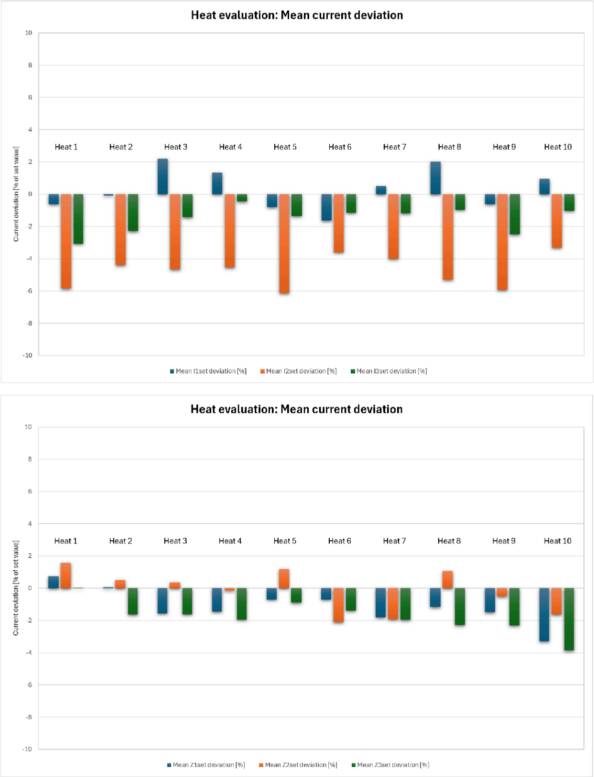


Figure 17. Current and Impedance phase deviations as a percent of the set value in the evaluated heats.

For the final selection of the optimal controller settings of the surveyed area, the dependences of all analyzed heats were observed. The chosen settings were based on the development of both energy consumption and impedance deviation during commissioning.

The selected parameter settings are listed in the following table.

Table 5. Final PID-settings

P-part	K_{P1} Positive	0.8
	K_{P1} Negative	0.66
	K_{P2} Positive	1.2
	K_{P2} Negative	0.93
	K_{P3} Positive	2.0
	K_{P3} Negative	1.14
	Deadband	1%
I-part	T_N	5000 ms
	Deadband	0%
Overcurrent control	Case 1	110%
	Case 2	130%

3 CONCLUSION

The ISEC was successfully commissioned at Vale Onça Puma. It is one of more than one hundred ISEC installed worldwide.

A final evaluation and heat analysis were carried out. The recorded deviations were relatively small, indicating good adherence to the set point. Most values fell within ±5% of the set current, a range considered acceptable in many furnace operations.

Individual customized reporting & analyzing tools will enable the operation and process teams to analyze and improve the ladle furnace performance.

Benefits such as increased productivity, enhanced energy efficiency, and reduced electrode- and refractory- consumption will ensure a rapid return on investment.

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