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Direct Feed to Enhance Power Quality and EAF KPI

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Decarbonizing steelmaking is one of the greatest challenges facing the steel industry today. Electrifying steel production is a pivotal step in reducing CO_2 emissions. Over the coming years, the installed base of high-power EAF is expected to grow significantly, which will affect power quality but also EAF performances. To address these challenges, GE Vernova has developed an innovative solution.

The Direct Feed system connects directly to the grid, enabling precise and highly stable electrode current regulation.

Design of the Direct Feed system will be presented with performance results derived from simulations and on-site measurements. Key outcomes, including improvements in EAF flicker reduction and operational performance, are highlighted.

KEYWORDS: STEELMAKING; EAF; POWER SUPPLY; DECARBONIZATION; ELECTRIFICATION;

INTRODUCTION

BF	Blast Furnace
BOF	Basic Oxygen Furnace
EAF	Electric Arc Furnace
ESF	Electrical Smelting Furnace
OSBF	Open Bath Furnace
DRI	Direct Reduced Iron
HMMR	Hybrid Modular Multilevel Rectifier
MMC	Modular Multilevel Converter
HVDC	High Voltage Direct Current
IGBT	Insulated-Gate Bipolar Transistor
THD	Total Harmonic Distortion
PCC	Point of Common Coupling
ΔU	Voltage variation
ΔI	Current variation
AC	Alternating Current
DC	Direct Current
KPI	Key Performance Indicator
FFT	Fast Fourier Transform
P	Active power
Q	Reactive power
I	Current
U	Voltage
δ	Depth of penetration
σ	electrical conductivity
f	frequency
X	Inductive reactance

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L	Inductance
D	Diameter
J	Current Density

THE CHALLENGE OF THE STEELMAKING ELECTRIFICATION

With around 2t CO_2/t of steel, the iron and steel industry is responsible for around 7-8% of the total CO_2 emissions in the world (figure 1).

These high carbon emissions are mainly due to the BF-BOF route: 71% of the global steel production with 2.33 t CO_2/t of crude steel. On the contrary, the EAF route produces less than 1 t CO_2/t of crude steel (for scrap based) but represents only 29% of the world production (including DRI based) [2].

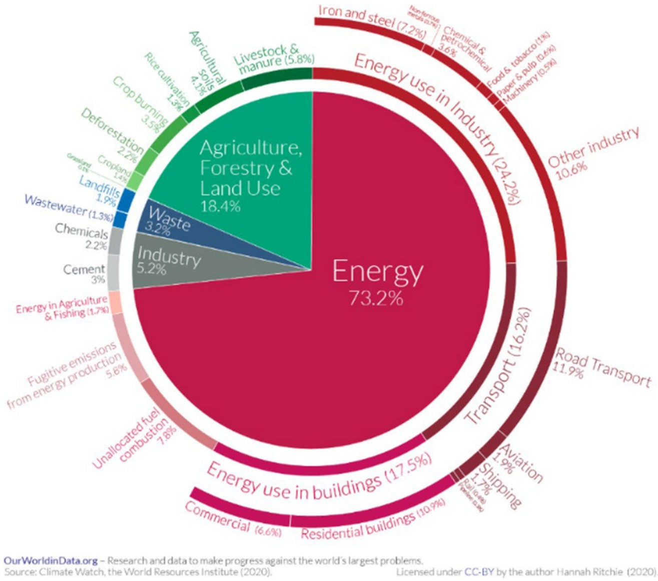

Fig.1 - Global greenhouse gas emissions by sector – Our World in Data [1].

Through 2030, OECD is expecting an increase of the world steel demand around 0.9% and emerging markets, excepted China, are planned to have a rebound in the steel consumption [3].

To decarbonize the industry, all the Net Zero scenarios are based on the energy production from renewable energy associated to the electrification of the industry [5].

In the ironmaking and steelmaking industries, electrification is also one of the pillars of decarbonization. All the future routes that are in development are based on process using electricity:

- iron ore electrolysis for direct production of iron from iron ore;
- water electrolysis to produce hydrogen for H-DRI production;
- smelters (ESF/OSBF) to produce hot metal from DRI;
- EAF for melting and refining.

The EAF process has the advantage of being already in operation with DRI and scrap with low CO_2 emissions. It will be used to melt solid iron produced by electrolysis or H-DRI and to replace the existing BF-BOF routes. In consequence a high increase of steel production through EAF is planned (figure 2). Wood Mackenzie is expecting an increase up to 48 % of the world production in 2050. The EAF deployment has already started. Today, most of the investments to increase steel capacity are done for EAF as presented by OCDE in figure 3.

This steelmaking revolution will be associated with several challenges:

- steel quality: to produce steel with low P, S, N, C content in EAF requires high quality materials leading to tensions on high quality scraps and DRI produced from DR grade iron ore;
- productivity: to match with BF-BOF productivity the tap-to-tap time of EAF needs to be optimized;

- furnace size: to match with BF-BOF capacity, the size of furnaces must be increased significantly leading to issues on power supply and power quality.

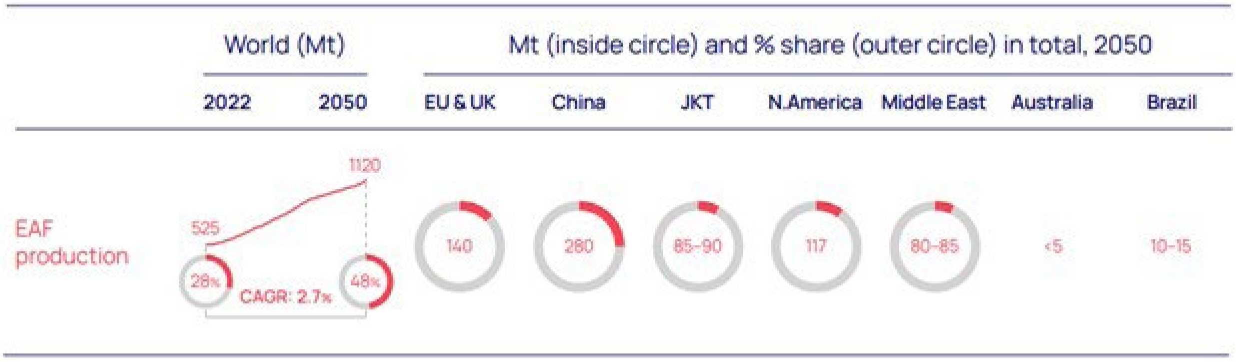

Fig.2 - Prediction of EAF production in 2050 – Wood Mckenzie [4].

In parallel, the International Energy agency is expecting a high increase in renewable energy as described in figure 4. The simultaneous growth of renewable energy penetration and EAFs operation poses a complex challenge to power system stability and power quality. Renewable energy leads to inertia and short-circuits reduction, limiting the grid's ability to withstand disturbances. In parallel, EAFs introduce large and non-linear loads that generate severe flicker and harmonic distortions and rapid voltage and active/reactive power fluctuations.

In other words, the future of steelmaking, driven by increased EAF production and higher renewable energy penetration, will face important power system challenges in addition to process related issues like availability, productivity and quality of raw materials.

To deal with these challenges, GE Vernova developed a power supply solution called Direct Feed [8].

Unlike conventional EAF installations relying on passive compensation with SVC and Statcom [9], the proposed approach leverages high-power power-electronics converters directly connected to the grid. This architecture enables active impedance control and precise electrode current regulation, significantly improving arc stability and furnace operational KPIs. In addition, the Direct Feed configuration contributes to improved grid power quality by reducing disturbances such as flicker and harmonic distortion. This work therefore demonstrates a new paradigm for grid-friendly large-scale EAF electrification based on power electronics.

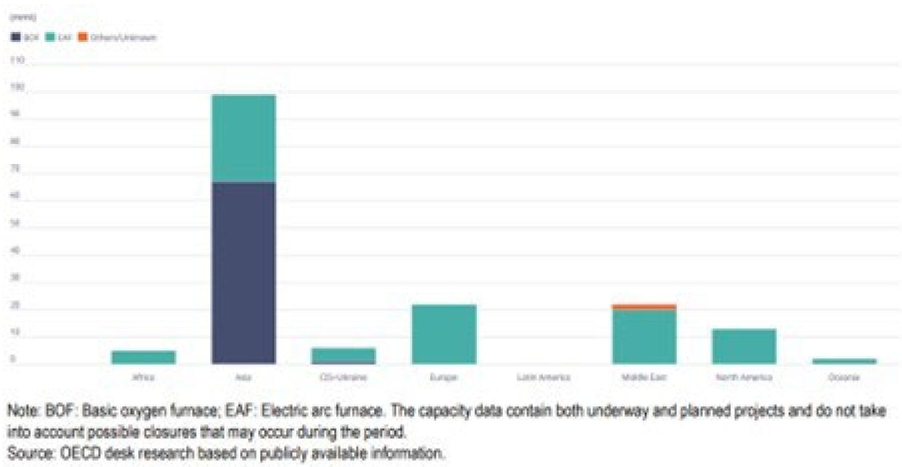

Fig.3 - Project of invest for new steel capacity according to BOF, EAF and others technology [3].

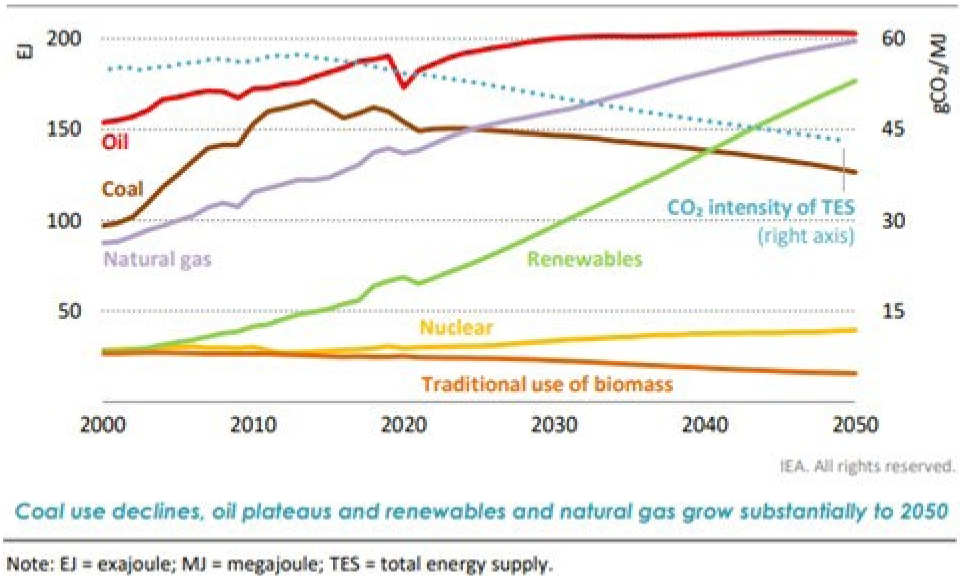

Fig.4 - Evolution and estimation of energy production by sources between 2000 and 2050 [5].

DIRECT FEED: MEDIUM VOLTAGE TECHNOLOGY

Direct Feed is a Medium Voltage (MV) Multilevel Modular Converter (MMC) based on a patented solution made of an MMC active front end rectifier (Grid converter) and a MMC Inverter (EAF Converter), more frequently referred to as back-to-back (B2B) converter (figure 5).

The MMC technology has been trusted by the Grid industry for more than a decade. It has been widely used in HVDC in the 300-500 MW range all around the world and more recently up to 1GW [6].

The same technology has also been used very efficiently in EAF and Grid Utility Statcom to address flicker issue. Building on a decade of experience and technology maturity, the Direct Feed for EAF is intended to bring Grid and EAF performances together towards a more efficient and more sustainable steel industry.

Direct Feed allows complete control of energy transfer from the grid to the EAF by controlling:

- current;
- voltage;
- impedance;
- frequency.

The standard MMC back-to-back converter used in HVDC application is designed to provide a bidirectional power flow unlike in EAF where the power only flows from the grid to the furnace. To this end, GE Vernova developed a patented solution to optimize the design of new converter for EAF.

By combining actively switched MMC submodule (IGBT) to diode rectifier building blocks, the hybrid solution provides both AC and DC current controls to the input grid converter while reducing the converter overall volume its volume, weight as well as increasing its efficiency.

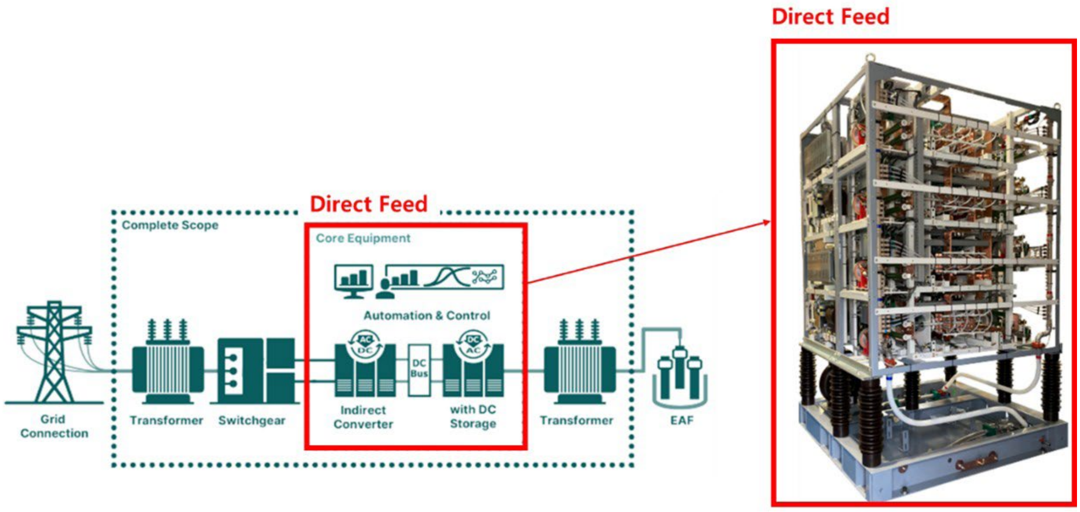

Fig.5 - Direct Feed technology: Medium Voltage solution to decouple EAF from the grid.

The Grid converter of the Direct Feed and the dedicated DC bus (figure 5) allow for the decoupling of the EAF operation from the grid supply, increased flicker reduction level far above standard Statcom, while maintaining a unity power factor on the grid supply.

The use of MMC topology also features total compliance with IEEE 519 and very high reliability with built-in redundancy.

The EAF converter provides very fast dynamic response thanks to the MMC topology coupled to powerful functions to accurately control voltage, current and frequency.

ADVANTAGES OF THE ACTIVE GRID RECTIFIER INSTEAD OF DIODE FRONT END

To decouple the EAF from the grid, the EAF Power Supply must be connected in series with the EAF [7] and use a DC link to store energy and act as a buffer. The EAF will draw reactive power from the DC link capacitor effectively avoiding the AC grid to provide for it. Similarly, the DC Link will also provide buffering for the active power drawn by the EAF. The buffering effect is the primary benefit towards reducing the flicker produced by an EAF when it is conventionally AC coupled to the grid.
The EAF Power Supply can either be connected to the primary side of the EAF transformer (Medium Voltage) or on the secondary of the EAF Transformer (Low voltage) (figure 6).

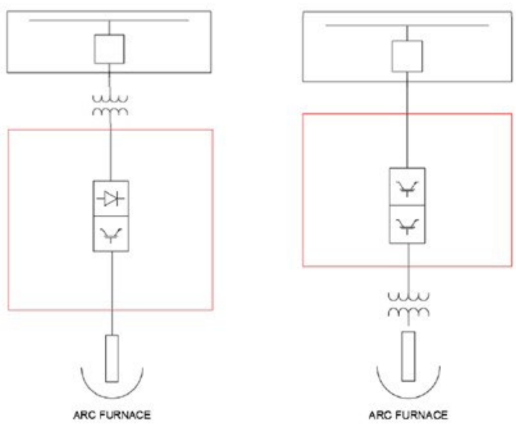

Fig.6 - CSerie Connected EAF Power Supply at secondary with DFE (on the left) and at primary with Direct Feed (Hybrid MMC) (on the right).

The simplest way to form a DC link is to use a Diode Front End (DFE) rectifier which can be made of several groups of 3-phase 6-pulse rectifiers (6, 12, 18 up to 36 pulses). This technology is well-known and robust for AC/DC applications. Typically, multi-pulse rectifiers are used to reduce harmonic distortion created by the rectifier.
Contrary to Direct Feed technology, A DFE has a limited maximum power factor and typically requires a multi-winding transformer (12 pulses and above), with the proper shifting phase.

The power factor depends on the winding impedance and can be calculated by using the transformer short circuit voltage $U_{k\%}$.

$$cos\varphi = 1 - \frac{\pi}{6} U_{k\%} \qquad [1]$$

Table 1 provides a reference based on common $U_{k\%}$ values. Although the power factor remains high, the reactive power consumption may vary between 30 and 40%.

Tab.1 - Rectifier transformer power factor.

Transformer Impedance Uk%	7%	10%	12%	15%
Power Factor Cos ϕ	0.96	0.95	0.94	0.92
Reactive Power	0.27 x Pn	0.33 x Pn	0.36 x Pn	0.4 x Pn

The transformer impedance will also create a voltage drop on the DC link that is not actively controlled.

$$\Delta Vdc = \frac{3}{\pi} X_{tr} I_{dc} \qquad [2]$$

The DC link voltage magnitude will vary along with the EAF load profile, translating into grid voltage magnitude variation and impacting the input current harmonic magnitude as well.

In some instances, a reactive power compensation system (RPC) or an active filter may be needed to address the remaining flicker and diode rectifier harmonics. That is not necessary for Direct Feed technology.

Replacing a DFE with a Hybrid MMC grid-controlled Rectifier (HMMR) allows to address the power factor and ensures an accurate control of the DC link regardless of the EAF load status. The HMMR topology also reduces the number of MMC submodules by 33% versus a standard MMC rectifier used in B2B converter. The power delivery from grid to the EAF is smoother and the grid will only provide active megawatts. MMC harmonics level are minimum and pushed far into the high frequency range thanks to the switching strategy and interleaving of the PWM carriers.

An MMC EAF Power Supply connects in series with the EAF on the primary side of the EAF Transformer and connects to AC bus commonly called "dirty bus". Additional energy storage within the grid side rectifier submodule can be used to provide partial var compensation for the Ladle Furnace.

MMC topology is meant to connect transformerless to a grid supply.
Direct Feed does not require any proximity with the EAF which simplifies green field plant layout. Equally, retrofitting an EAF with such solution is also possible. The existing EAF furnace can be reused as it is without any modification while the MMC Converter can be installed near the HV/MV switchyard.
Installation of a MV equipment also presents some advantages in plant design due to the lower current requirement. Direct Feed doesn't need to be close to the furnace and can be installed up to 1.5 km of the furnace.
EAF will also benefit from the embedded redundancy within the MMC designs allowing them to reach >99%

availability as successfully demonstrated in other industries.

GRID SIDE: POWER QUALITY IMPROVEMENTS

As it is a technology proven and proposed by GE Vernova for decades in other industries, the development of the steel industry and the EAF has been very fast between the development in 2021 and the first installation in 2024 when the commissioning started.

Today Direct Feed is in operation with 100% of the heats running with Direct Feed. Some results can be shared and show an impressive improvement of power quality when Direct Feed is turned on.

Figure 7 shows high flicker reduction above 9 (last assessment shows Flicker reduction between 10 and 11) and low Total Harmonic Distortion, below 1.5% which results from the decoupling between Direct Feed and EAF. An example of voltage spectrum is given on figure 8.

These results are very important for power quality requirements but also for EAF performances. Thanks to Direct Feed, the EAF is no longer constrained by the grid side. In lot of plants, EAF current set points are limited by flickers impact; with Direct Feed, it is now possible to work at the maximum current set point without any negative impact on Flickers and the grid.

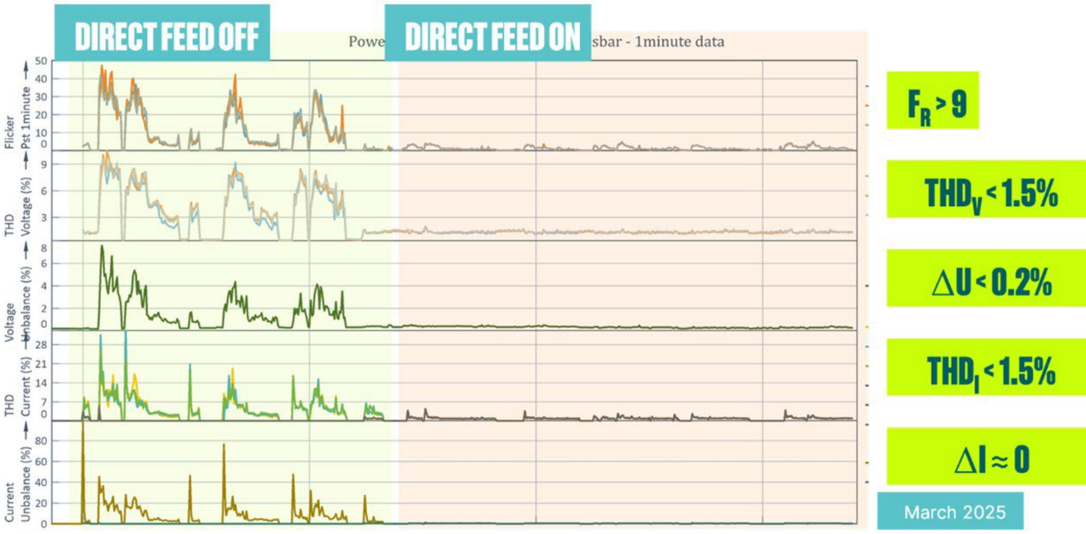

Fig.7 - Effect of Direct Feed on power quality.

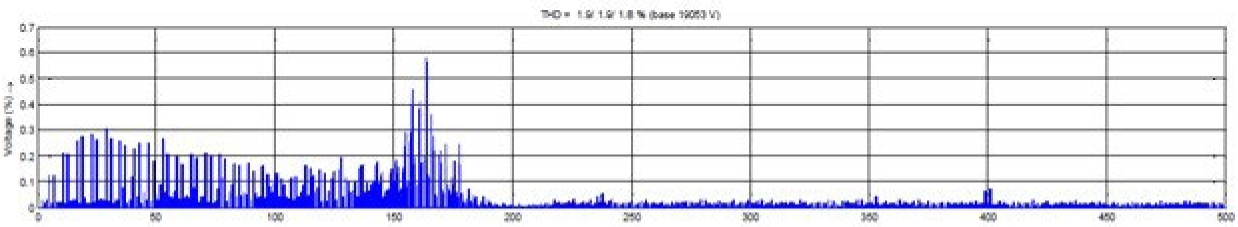

Fig.8 - Harmonic Voltage spectrum.

Actively controlling the grid power factor to unity remove the risk of the grid voltage drop due to reactive power consumption, unlike a DFE rectifier, as mentioned before. When Direct Feed is OFF, the grid voltage drops by 6kV whereas when the Direct Feed is ON, the grid voltage remains stable (figure 8).

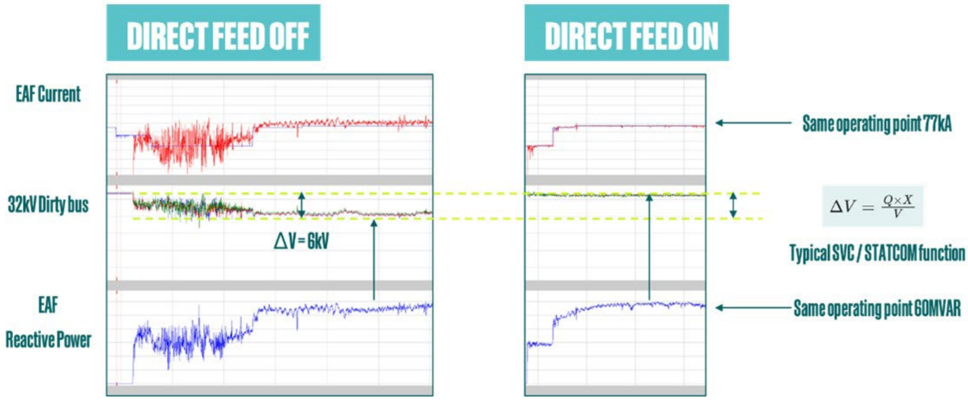

Fig.9 - Effect of Direct Feed on grid voltage stability.

EAF SIDE: KPI IMPROVEMENTS

Direct Feed is not only designed to improve power quality but also to improve EAF performance. The main drivers to enhance EAF KPI are:

- improvements of arc stability;
- frequency control;
- direct control of electrical parameters without transformer taps.

Considering all the benefits provided by Direct Feed that are presented in the next pages, the main EAF KPIs can be improved.

- Productivity has improved thanks to a reduction in Power-on time around 10%.
- Energy consumption has decreased around 5%.
- Electrode consumption is around 10%.

Of course, these values can vary from one plant to another, and specific assessments have to be made.

Improvement of arc stability

Arc is stable when the dissipated power is sufficient to maintain it by ensuring the ionization of the gas and the current to pass. The cause and consequence are significant changes in voltage, current, power and grid.

Several causes can be responsible for arc instability such as scrap quality, electrode position, cold furnace, gas composition, melting process, and electrical parameters.

During AC EAF operation the electrode behaves alternatively as cathode and anode. During one half wave, the current is negative, and electrode is anode, and the arc is stable forming a continuous plasma jet between the electrode and the steel bath. During the next half wave, the current becomes positive, and the electrode becomes cathode (figure 9). At this stage the plasma jet is less stable.

Instability is also due to the transition between anode and cathode when current is crossing zero. The transition is not instantaneous and is accompanied by arc extinction and arc reignition (figure 9). The more the delay between extinction and reignition, the more the instability. Even if the delay is short (a few ms), as the current is crossing zero several times by second (depending on frequency), for an entire heat the impact can be high.

Thanks to Direct Feed, this delay is minimized by controlling directly the current and by adapting the voltage waveform to fit to the non-linear behavior of the arc and by maximizing the arc voltage when the current is crossing zero.

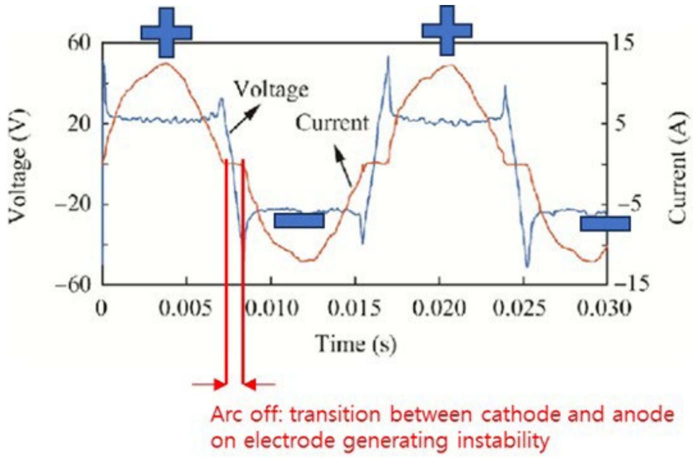

Fig.10 - Typical current and voltage waveform of AC EAF.

Simulation results for two kinds of furnaces, moderate and large perturbations, are presented in figure 10.
With Direct Feed (current control), the current fluctuations and extinctions are much lower compared to conventionnel operation (without Direct Feed) leading to higher energy input for the same duration due to higher power. The more unstable the furnace is, the higher the gain.

Thanks to current stabilization, Direct Feed offers a power margin that can be used to:

- reduce power on time and increase productivity;
- target lower current set point to decrease electrode consumption and electrical losses;
- target lower voltage set point to decrease arc length and arc radiation.

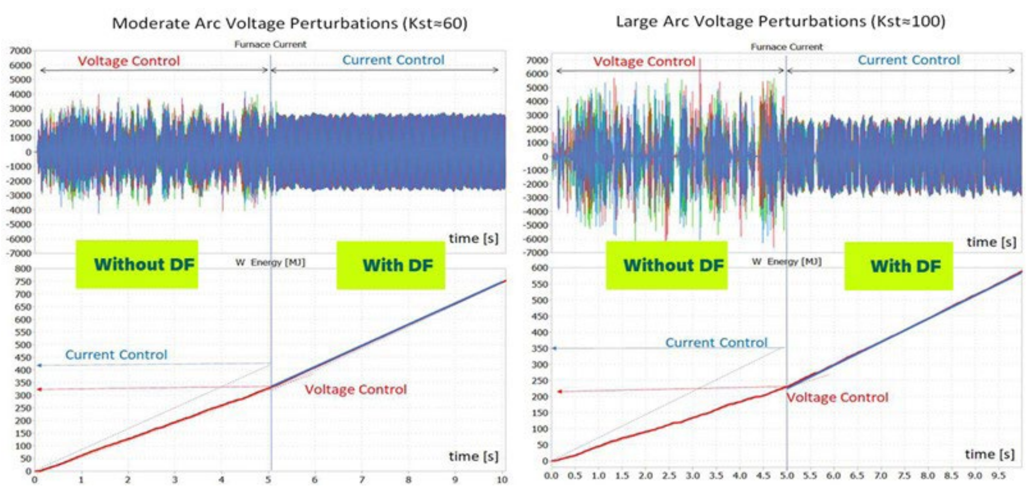

Fig.11 - Effect of Direct Feed on moderate arc voltage perturbations (on the left) and large arc voltage perturbations (on the right).

Impact of Direct Feed on 150 t industrial furnace is described in figure 11. When Direct Feed is turned ON, the current deviation around the reference becomes close to zero whereas when Direct Feed is turned OFF, deviations are between -10 and + 5 kA.

Additional increase in arc stability can be performed by increasing frequency.

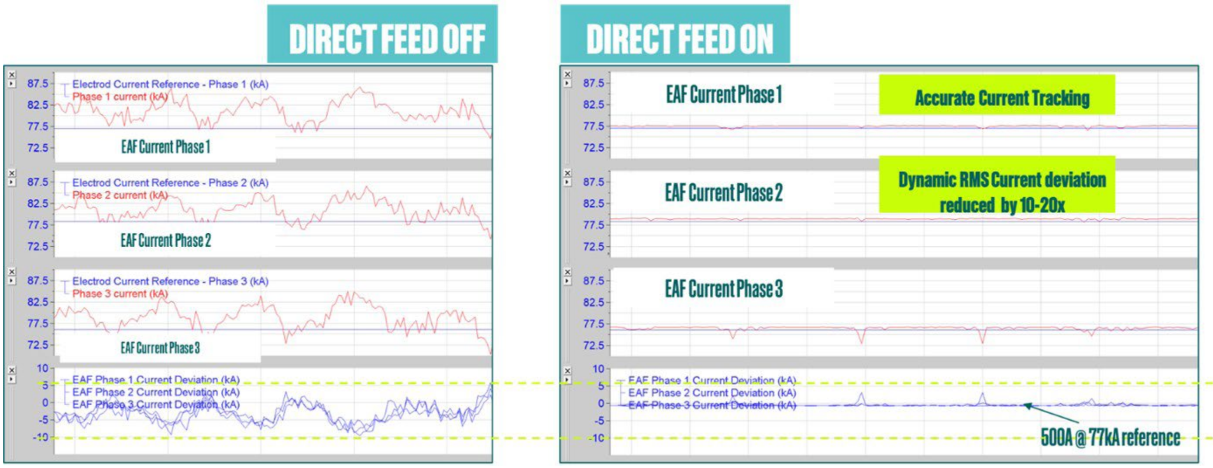

Fig.12 - Effect of Direct Feed on electrodes current.

Frequency control

According to the capacity of the transformers, Direct Feed allows frequency control. Thanks to frequency variation it is possible to adapt the strategy of the EAF to the desired KPI.

The equation 3 shows that frequency influences the reactance and consequently the arc stability because when reactance increases the arc stability increases. Increasing reactance leads to increase phase shift and so decreases power factor.

$$X = 2.\pi.f.L \quad [3]$$

In addition, frequency influence EAF performances through the skin effect. When frequency decreases the skin depth increases leading to lower resistance and lower current density (equation 4). Equations 5 and 6 show the relationship between skin depth, resistance and current density.

$$\delta = \frac{1}{\sqrt{\sigma\mu\pi f}} \quad [4]$$

$$R = \frac{1}{\pi D\delta} \quad [5]$$

$$J = J_S e^{\frac{-(1+j)d}{\delta}} \quad [6]$$

Consequently, for the process, the best practice will be (figure 12):

- in the first minutes of the heat, during boring, to start at high frequency to increase reactance and decrease power factor to increase arc stability;
- then, decrease frequency to reach minimum frequency in flat bath/refining phase in order to minimize electrical losses and electrode consumption.

In this way, thanks to frequency variation, the EAF process can be optimized according to the different steps and needs of the melting process.

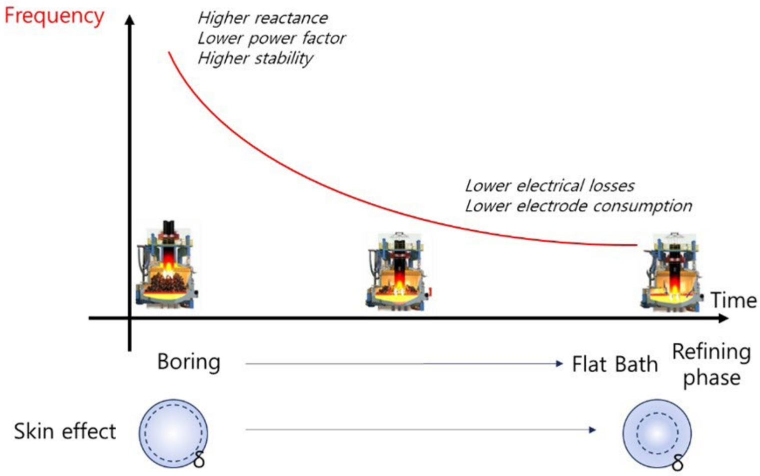

Fig.13 - Frequency management during one heat thanks to Direct Feed.

Thanks to Direct Feed capabilities, new operating set points are possible according to the frequency.

As presented in figure 13, decreasing frequency leads to an increase of power factor at constant power and current set points. So, it is possible to operate the furnace at the same power and current but with different power factors. In the same idea it is possible to operate at constant power factor and arc length to target higher power.

It offers to the steelmakers the possibility to redefine the current, voltage and power set points in order to target a specific objective of performance—such as energy consumption, productivity, electrode consumption, refractory wear, etc.—and consequently the flexibility to adapt the EAF practice to the specific constraints of the EAF.

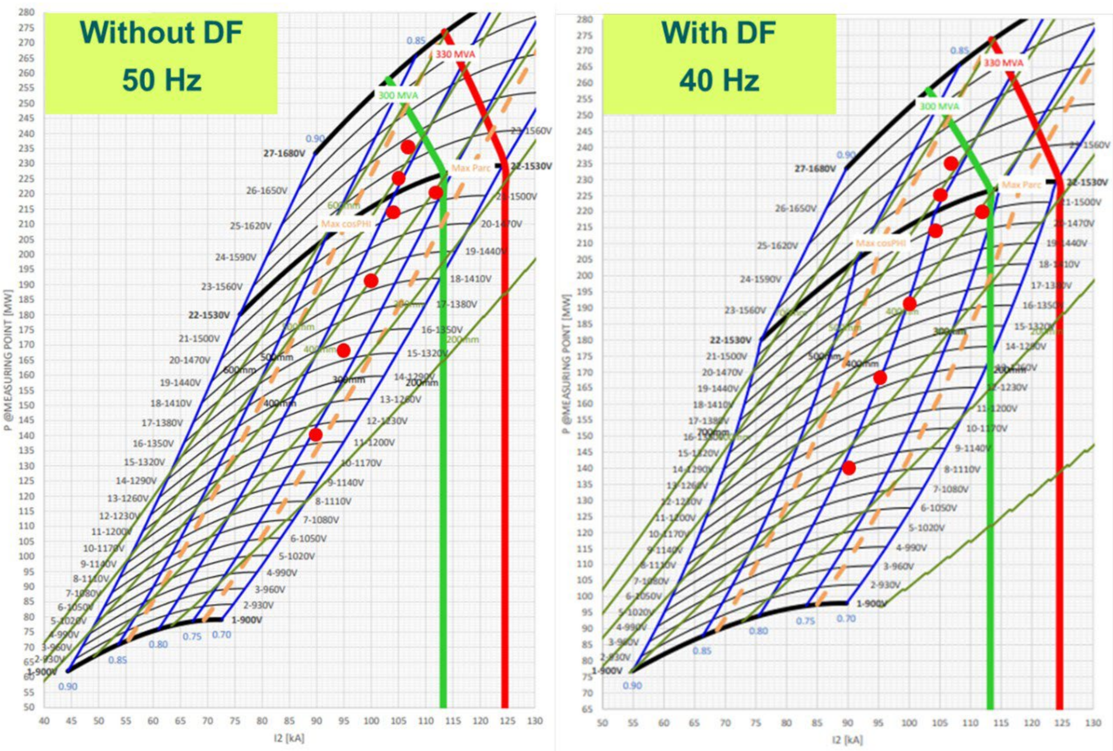

Fig.14 - Effect of Direct Feed on electrodes current.

Additional benefits: flexibility of EAF practice thanks to Direct Feed

With Direct Feed, transformer tap changes are not necessary. Direct Feed can run with tap changer but is not necessary because now with Direct Feed current, voltage, power, and frequency are directly controlled, very quickly and very precisely. Consequently, the EAF can be operated in a much smoother way without abrupt change of tap, current, voltage and power.

In addition, with Direct Feed, voltage and current on each electrode can be controlled independently leading to several benefits for the process. For instance, it is possible to adjust the electrical parameters of one electrode to decrease its arc length and prevent high arc radiation to decrease refractory wear close to this electrode without impacting stability or power input.
The power margin created by Direct Feed also allows to charge lower quality materials that require higher energy to be melted. Arc length can be lowered in order decrease slag height and save fluxes, at constant power factor.
For continuous furnace, like Consteel furnace (provided by Tenova), Direct Feed allows optimization of power ramp-up to promote fast slag formation to prevent arc radiation and refractory wear.

In other words, Direct Feed allows for improved control of the furnace and extends the operational performance limits. Given that each plant or furnace has its own specificities, the flexibility of Direct Feed represents a key advantage in reaching the objectives.

CONCLUSION

The electrification of the steel industry is a key lever for reducing global CO_2 emissions and enabling the transition toward low-carbon steel production. However, the increasing deployment of high-power EAF installations introduces significant challenges in terms of grid stability and power quality.
This paper presented the Direct Feed concept developed by GE Vernova, which replaces the traditional transformer-based EAF supply architecture with a power-electronics-based solution directly connected to the grid. The proposed approach enables precise and highly stable electrode current regulation while significantly reducing disturbances such as flicker and harmonic distortion.
Simulation and industrial measurements show that the Direct Feed system improves both grid power quality and furnace operational performance. The capability of power electronics to actively control impedance and regulate electrode current provides a new paradigm for large-scale EAF power supply systems.

Direct Feed is a true game changer for EAF production, delivering significant improvements in both power quality and EAF performance. This technological breakthrough represents a major step forward, redefining the way EAFs are operated while minimizing their impact on the grid.
By decoupling EAF from grid, very high Flicker reduction and very low THD can be achieved.
By controlling directly the electrical parameter, significant key EAF performance indicators can be enhanced.

Direct Feed opens the way to a new standard in EAF operation, combining flexibility, efficiency, stability and sustainability.
In the next years Direct Feed will be installed in several steel plants including ultra-high-power EAF. The world's largest AC EAF at 360 MVA will be equipped with Direct Feed. As steel plants continue to increase furnace power and productivity, the capability of power-electronics-based supply systems to maintain stable electrode current control while minimizing grid disturbances will become increasingly important.

In addition, the next step will be the integration of Battery Energy Storage (BESS) directly connected to the DC bus of the Direct Feed systems. The addition of battery storage will provide several advantages like load shifting, power shaving, and will add additional flexibility by buffering fast power fluctuations generated by the EAF process. Such an approach would further improve grid stability by smoothing transient power variations and reducing peak power demand from the grid.

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