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Next generation direct feed power supply for large steelmaking EAFs

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The expansion of EAF production, alongside with the large-scale deployment of renewable energy sources, has significant impact on network stability and local capacity. Steel producers are facing growing pressure to minimize disruptions to the electrical grid and meet ever increasing utility requirements. To tackle these challenges a novel multilevel converter for the decoupling of EAF operation from the medium voltage grid supply was developed, installed and commissioned in a German steelmaking plant in December 2024. This Direct Feed (DF) Power Supply enables steelmakers to increase both power quality and EAF performances. Key benefits demonstrated during full heat cycle operation in the nominal power range (up to 130 MW) include a flicker reduction factor above 10, EAF operation with individually controlled electrode currents, and related EAF performance and operational flexibility benefits that are highlighted in separate EEC 2026 conference papers [1, 2]. Thanks to the gains in controllability, power quality and EAF performance, five large steelmaking plants have decided to build on this new type of MV MMC DF power supply, the largest one is a 340-metric-ton Consteel EAF that will support the customer's target to achieve carbon neutrality by 2050.

KEYWORDS: MODULAR MULTILEVEL CONVERTER; MMC; ELECTRICAL ARC FURNACE; EAF; FLICKER REDUCTION; POWER FACTOR; ELECTRODE CURRENTS; ARC STABILITY; DECARBONIZATION.

INTRODUCTION

Historically, utility requirements have been sufficiently satisfied with the use of Static Var Compensators (SVCs) and STACOMs connected in parallel to Electric Arc Furnaces (EAFs), which correct the power factor and reduce harmonics, flicker, and unbalance conditions. In the past decade, dynamically controlled STATCOMs have become "the new normal" solutions for furnace compensation with harmonic reduction of 2x-3x for most harmonic orders and flicker reduction of up to 5x or 6x [3, 4]. To date, STATCOMs have been able to meet the utility requirements for harmonic, flicker, voltage unbalance, and power factors. However, when higher power quality of the EAF is required due to a weaker grid supply, in case of very large EAFs with a nominal power above 300 MVA, or a combination of both, the need to electrically decouple the EAF from the network proves more efficient. The use of a converter connected in series to the EAF achieves higher performances than a parallel connected solution like a STATCOM. By decoupling the EAF operation from the grid supply, a Direct Feed (DF) power supply dras-

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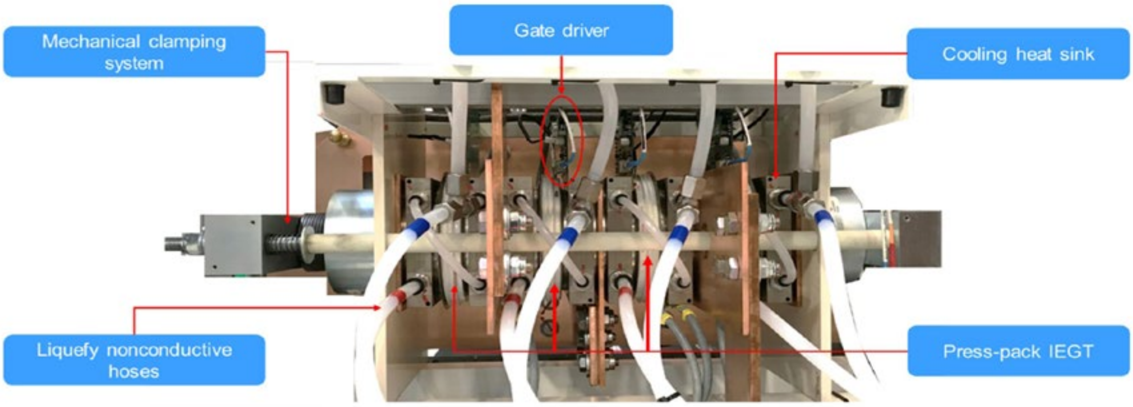


Fig.1 - Power stack with 4 IEGTs used in MV drives and MV MMC power cells (HB and FB submodules).

tically improves the flicker reduction level while maintaining a unity power factor at the EAF MV feeder [5]. The use of a Modular Multilevel Converter (MMC) topology guarantees total compliance with IEEE 519 and very high reliability because of the modular design with n+1 or n+2 redundancy in each converter arm.

DIRECT FEED CONVERTER DESIGN FOR EAF APPLICATIONS

To achieve high robustness and ampacity of the individual power submodules, the DF converter design is based on proven press pack IEGT (PPI) technology that has been used in MV drives for about 20 years [6]. PPIs are pressure-welded high-power devices with built-in IEGT chips. Latest generation Trench devices are used to provide minimum losses and high reliability of the actual switching devices of the converter. Figure 1 shows an example of a press-pack stack with 4 IEGTs. The single IEGTs have a 4.5 kV nominal voltage, with several current ratings available, mainly 750 A, 1500 A, 2000 A and 3000 A. This technology is the base of creating full bridge (FB) and half-bridge (HB) submodules. The power stacks are cooled by deionized water. Each IEGT benefits from double side cooling. Another benefit of press-pack stacked IEGTs is that the main failure mode is a maintained short circuit, which makes the redundancy implementation easier, and avoids the necessity for arc containment casing. This results in a compact and cost-effective design of the high-power density stacks, converter submodules and towers. A simplified version of the converter-based power supply is shown in figure 2. The EAF and grid side are decoupled by a DC link. The DF rectifier and inverter are both multi-level topologies (n = 16 resp. 24 per arm) to ensure high power quality in the MV networks. Figure 3 shows an installation example of a DF inverter. Each of three inverter arms consists of six HB towers with four power stacks (eight HB submodules) to provide a nominal power of 175 MVA to the furnace at a power factor of 0.75. Additional capacitor banks in the DC link provide additional energy storage and de-coupling between the EAF load and the grid.

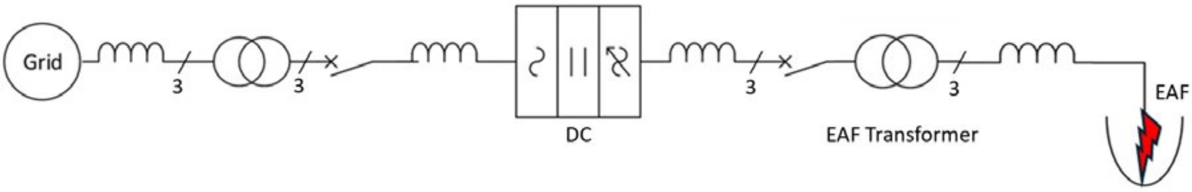


Fig.2 - Simplified Circuit Diagram of EAF MV Power Supply based on AC/DC/AC (DF) Converter.

Fig.3 - Photo of the 18 HB towers that interlink the DC bus of the DF converter with the EAF transformer via three arm inductors. Each HB tower contains four power stacks.

EAF POWER QUALITY AND DF CONVERTER CONTROL CHALLENGES

The mitigation of arc furnace perturbations provides an extreme load scenario for MV equipment. The main control task challenge is to compensate for the arc furnace impact on the grid during electric arc heating, including the reduction of flicker effects. The (non-regulated) currents from the arc furnace during a heat cycle are very unpredictable (erratic, asymmetric, fast variation). Peak currents during electrode short-circuit conditions can reach values above 100 kA for large directly grid-connected furnaces that are operated without current control. To control the furnace currents and actively compensate the power fluctuations caused by the arc voltage fluctuations, a converter control system with very fast response behavior is required. It is achieved by a distributed control architecture, which reduces the amount of data exchanged with the global control system and optimizes the calculation capacity of the local and global control. The main benefits of the distributed control principle is that sampling periods of the current control loop below 40 μs are achievable on the inverter side, which is one order of magnitude lower than what is required to control the effective value of the electrode currents to be constant and avoid overshoots of the electrode currents in case of a short-circuit (e.g. if the electrode comes in contact with scrap material). Thus, DF EAF supply systems offer unprecedented performances in the current regulation, which are not possible with a classical MV EAF power supply system, where the externally imposed supply voltage is constant and defined by the tap setting of the EAF transformer. Figure 5 shows a comparison of a full EAF heat cycle that has been simulated in a real-time simulation (RTS) test platform with the actual DF converter control system shown in figure 4 and a furnace model validated by customer site measurements.

Fig.4 - DF Converter Control in RTS test platform.

The electrode currents are individually controllable in a DF power supply; their effective values can be kept constant during the whole heat cycle. Only in the case that an arc voltage is required to be above the voltage limit of the DF inverter, the electrode currents may drop to zero. This is explained in more detail below, in section "Generation of Voltage Pulses to Assist EAF Current Zero Crossings". It is clearly visible with DF operation, there is no more overshoot of electrode currents under short-circuit conditions. It has been confirmed during almost 12 months of routinely operating a large steelmaking EAF with DF power supply that the max. electrode current amplitudes are 30 % lower than with a conventional EAF power supply. A 30 % reduction in peak electrode currents results in more than 50 % reduction in dynamic electromechanical forces, which significantly reduces the stress on the EAF transformer secondary windings and on the entire power supply network, which has a positive effect on equipment lifetime. Other benefits of DF power supplies are:

- independent control of the arc length and electrode current (which is kept constant by the converter);
- the AC/DC/AC converter decouples the EAF from the grid, no reactive power, harmonic and current imbalance can propagate from the EAF to the grid;
- no need for shunt compensation system; no more reactive power peaks on the grid side;
- buffer capacitors in the converter DC link provide partial filtering of active power variations;
- flicker mitigation factors significantly above those achievable with the STATCOM shunt compensation systems (>10);
- variable frequency EAF operation, e.g. 50Hz-60Hz during the perforation phase and 30Hz-40Hz during the refining phase to increase the overall process efficiency;
- increased production through tap-to-tap time reduction (EAF transformer tapping no longer required).

These benefits have been demonstrated in a large steelmaking plant in Germany since December 2024 with a DF power supply rated to provide 130 MW of nominal heating power. For customer information protection reasons, no absolute measurement values but only p.u. results can be shown in this paper. The measurements have been reproduced in the RTS platform shown in figure 4, after confirming by site measurements that the EAF load model represents the same operating conditions as the actual furnace, e.g. in using an arc voltage-current characteristic that depends on the EAF thermal state. In cold state of the EAF, the arc is more unstable, and electrode current interruptions may occur, causing unbalanced operation on the EAF side. An example for unstable operation during cold EAF conditions is shown in figure 6.

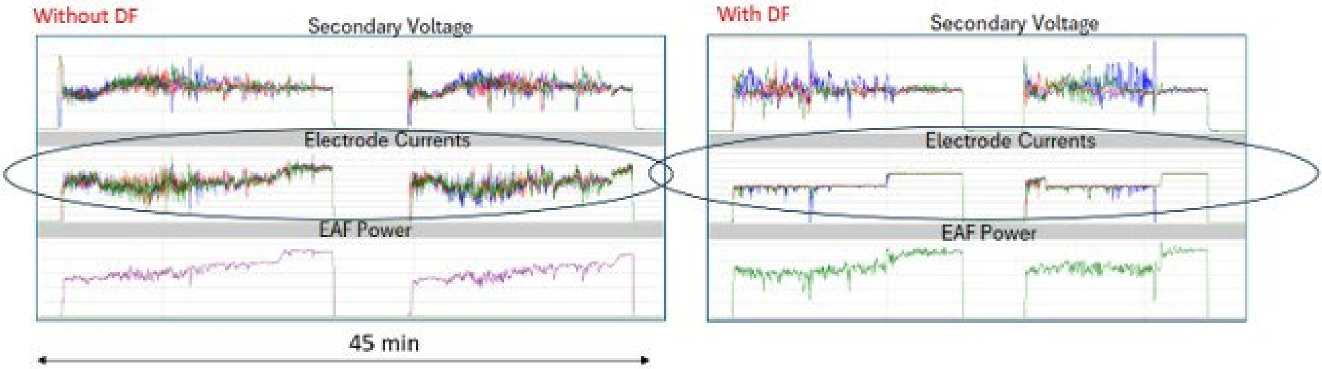


Fig.5 - Comparison of RTS measured values on the secondary side of the EAF transformer during a full EAF heat cycle without (left) and with DF power supply (right).

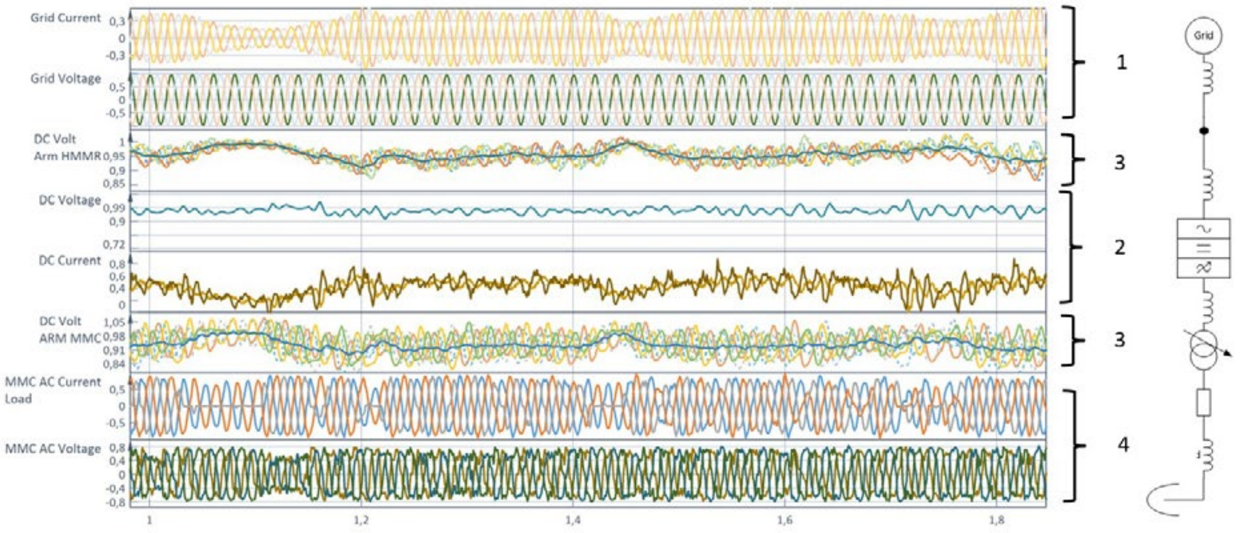


Fig.6 - Currents and voltages on the EAF side (4), in DF converter arms (3), in the DC link (2) and on the grid side (1) during EAF unstable operation with arc interruption.

Around the zero crossing of the electrode current, the arc is extinguished and is regularly re-struck after a certain time during the next half-cycle of the AC voltage, when the voltage with the new polarity has reached a certain value sufficient for arc re-firing. If the arc is not ignited immediately at current zero crossing, the arc current may be interrupted.

It is visible in the MMC AC currents of figure 6 that the single-phase arc interruption causes a temporary drop of the DC link current, whereas the DC link voltage is kept constant, which means that there is a temporary drop of active power supplied to the EAF during such electrode current interruption. On the grid side, the AC currents continue to stay perfectly balanced and the there is no visible effect on the grid voltages, also not at re-ignition of the electrode current or during other electrical transients on the EAF side, because the DC link prevents the propagation of reactive power and the DC capacitors included with each MMC submodule and in the DC link of the converter are able to provide a sufficient filtering of active power transients. In addition, and this is where MMC converters provide a substantial advantage in comparison to two-level or three-level voltage source converters, the multilevel converter generates voltages with an almost ideal sine-wave shape on the grid side, thus enabling full IEEE 519 grid code compliance without additional reactive power or filter circuits required. Exemplary values for power quality indices at the dirty bus of a large steelmaking EAF operated with and without DF power supply are shown in figure 7. For the quantitative evaluation of the flicker reduction factor achievable with DF power supply, site measurements considering all operating conditions must be conducted. Flicker reduction factors above 10 have been confirmed during the final EAF pilot plant performance measurements. DF power supplies take the power quality of electrical arc furnaces to a new level and enable EAF operation in comparably weak grids, e.g. substantially powered by renewable energy sources. They also enable EAFs with nominal power and heat size that exceed the capacity of conventional AC furnaces [7].

DF POWER SUPPLY FOR VERY LARGE AC FURNACES

Very large EAFs, exceeding the active power that can be provided with a single MMC DF converter with a rated voltage of 33 kV, can either be supplied by an MMC converter design with higher nom. voltage, e.g. 66 kV, or by a parallel connection of two DF converters of the same design as shown in figures 1-3. An example design for a DF power supply that can provide nominal heat power up to 250 MW is shown in figure 8.

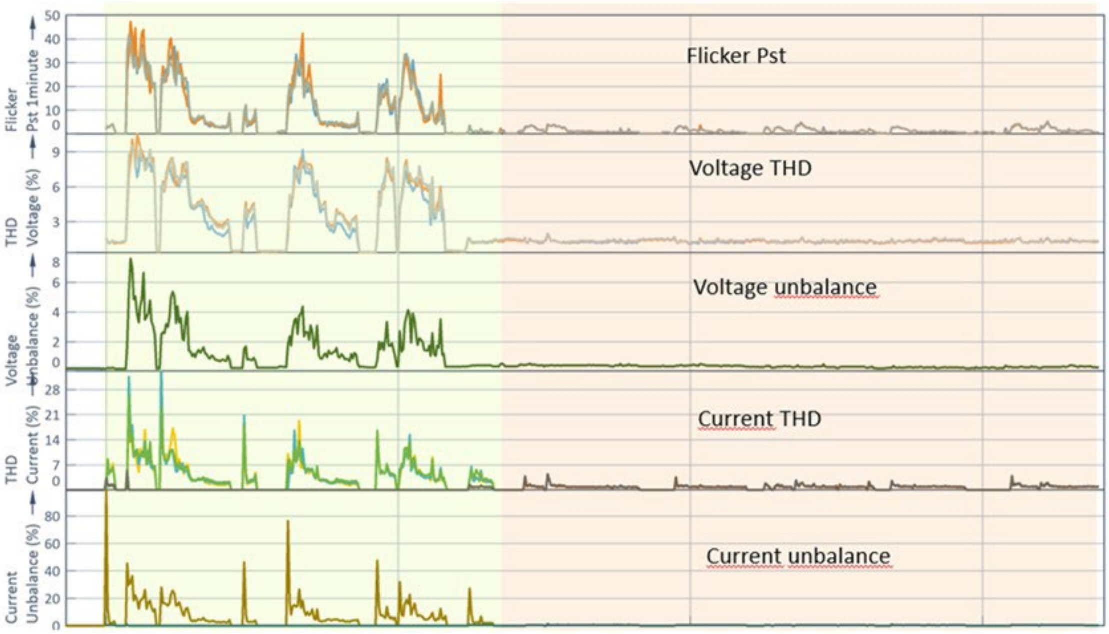


Fig.7 - Comparison of RTS platform measured power quality indices during a full EAF heat cycle without (left) and with DF power supply (right).

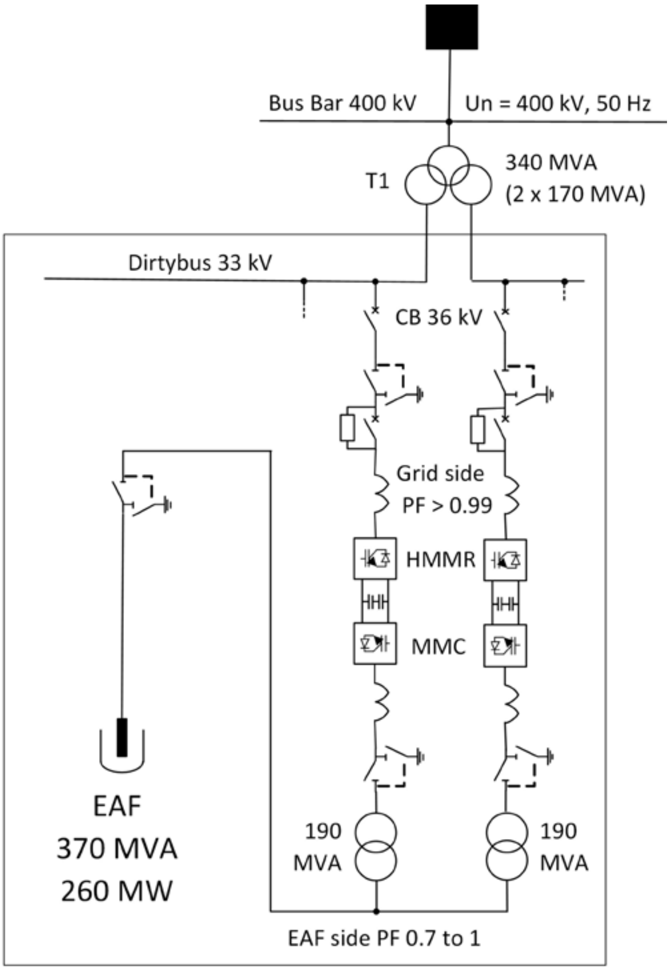


Fig.8 - DF Power Supply for very large EAF.

The larger the furnace, the more important are stable operating regimes. With a DF power supply, the arc length can be varied while the arc current is kept constant, thus enabling new process control strategies [6]. In addition, the furnace can be operated at frequencies other than the grid frequency, e.g. above 60 Hz during the perforation phase and below 40 Hz during the melting phase. While most of these operating regimes have already been successfully tested in the 130 MW DF pilot plant in 2025, the following two sections describe new functionalities that have been successfully demonstrated in simulations with validated model parameters and by measurements on an EAF plant operated with more than 100 MW of heating power - see pages 41 and 42.

GENERATION OF VOLTAGE PULSES TO ASSIST EAF CURRENT ZERO-CROSSING

In AC EAFs, at the electrode current zero-crossings, the arc temperature drops and the electron density in the arc column diminishes rapidly due to ion-electron recombination. Consequently, electrical conductivity of the plasma channel reduces exponentially. In the EAF cold state, within tens of microseconds, the arc can transit from hot plasma to weakly ionized gas. If the gas is largely deionized, the arc conduction cannot be easily established as arc reignitions may require nearly full insulation breakdown. Therefore, even with the closed loop current control by a converter supply system, the arc may fail to re-ignite the arc current. It may stay at zero after a zero crossing if the voltage applied by the converter immediately after current zero crossing is not sufficiently high to force reignition/reversal of the arc current with minimum delay before full de-ionization occurs. The voltage is the only physical variable that can restart the arc, while occurrence of the breakdown depends on the electric field strength (applied voltage / gap length), residual ionization and metal vapor concentration. In classical grid supplied EAFs, the EAF voltage follows the grid sinusoidal excitation and adequate voltage at EAF current zero crossings are provided by operating EAF with sufficiently low power factors. This ensures that the EAF current, which is lagging the supply voltage, has zero crossings at sufficiently high grid voltage in the opposite direction, supporting arc current reignition and current polarity reversal with a minimum delay. If the EAF power factor is high, delayed current re-ignitions or even totally missed conduction intervals could occur (arc instability), causing higher voltage flicker and harmonic distortion (including even-order harmonics due to arc current half-wave asymmetries).

To ensure robust arc re-ignitions at the current zero crossings regardless of the circuit fundamental power factor, the converter supplying the EAF can apply short additional voltage pulses prior to the current zero crossings [8]. With such voltage-pulse assisted re-ignition the residual ionization enables almost-instantaneous re-strike, continuity of the arc and stable power transfer. At the same time the voltage pulses can be short, limited and synchronized with the current (not applied as a brute-force voltage). Their purpose is just to exploit residual ionization. It is preferable to avoid using square voltage pulses and apply a short voltage ramp instead over a predetermined period (limitation of pulse DV/DT). This helps to encourage volumetric arc ionization, avoid filamentary breakdown, and reduce EMI effects. The EAF current zero crossing instants can be predicted, for example using the controller current reference or using the actual current waveform (for example setting a Phase Locked Loop on the EAF current). The predicted EAF current zero crossing instants can be used as base to define precise timing and shape of the reference for the voltage pulse to assist the EAF zero crossing. Optimal voltage pulse application is at or right after the electrode current zero-crossing, when electron density is reducing but it is still non-zero, and the required breakdown voltage is minimal. However, timing of the pulse voltage reference may be adjusted to consider the control, and the PWM converter delays, so that the instant of the applied voltage pulse is at its optimum. If the additional voltage pulses are applied too late, plasma may already be recombined and the required voltage is sharply increased, resulting in a miss to re-ignite the arc in a smooth way. The applied voltage pulse duration should be adjusted to a sufficient volt-second area, to force a current swing at the reversal up to a value needed to reignite the arc current (holding current):

$$V \times t_{pulse} = L\,\Delta I \qquad [1]$$

In the cold start of an EAF, the magnitude of voltage pulses will be relatively higher while in hot state with foamy slag, it will be low (or no pulse voltage assistance is needed). Depending on the available voltage margin, a trade-off between pulse magnitude and pulse duration can be made. The voltage pulse assistance can be readily implemented in the PWM converter control supplying the EAF. Precisely controlled and synchronized application of voltage pulses can advantageously supplement the current control loop of the converter. References of the voltage pulses can be, for example, added to the voltage references synthesized by the current control loop. Due to the relatively short duration of the voltage pulses the effect on the close loop current control is minimal. It is also possible to temporarily freeze the closed loop current control during application of the voltage pulses. With the voltage pulse assistance, arc reignitions become more deterministic for each half-cycle, and arc plasma continuity is maintained. The final effect is improved arc stability, reduced arc power oscillations and phase imbalances, lower arc current distortion (particularly reduced half wave asymmetry), reduced acoustic noise, reduced voltage spikes at the transformer, and better flicker performance at the PCC. The effect of applying such Assisted Arc Ignition (AAI) voltage pulses at the current zero crossings has been validated in real-time simulations, as shown in figure 9 and by EAF site measurements, as shown in figures 10,11 and 12. The arc current DI/DT at zero crossings is increased and corresponding improvements in the arc stability are obtained without the need to operate the EAF at elevated frequencies when it is in cold state. Thus, better system efficiency is expected.

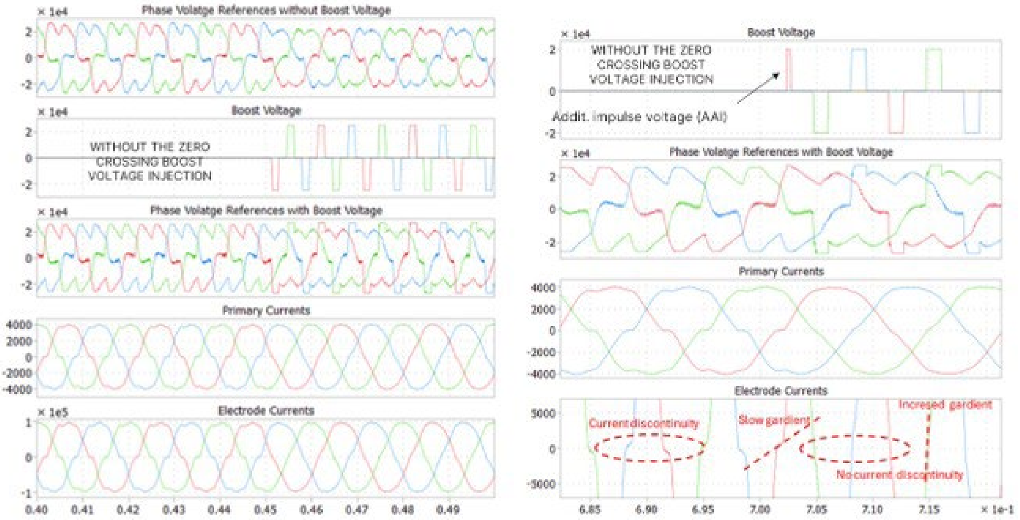
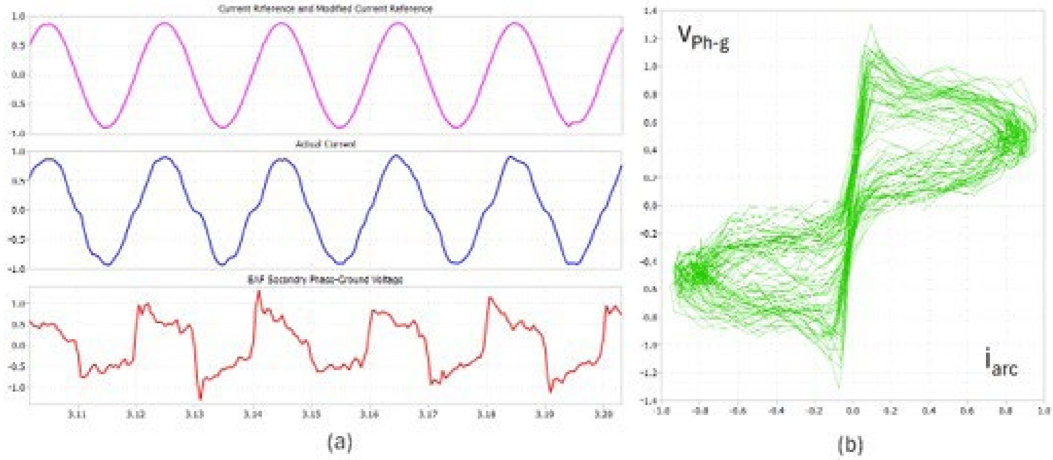


Fig.9 - Increase of electrode current di/dt during zero crossing by injecting additional voltage pulses.

FIRST FIELD TEST VALIDATION RESULTS WITH ASSISTED ARC IGNITION CONTROL

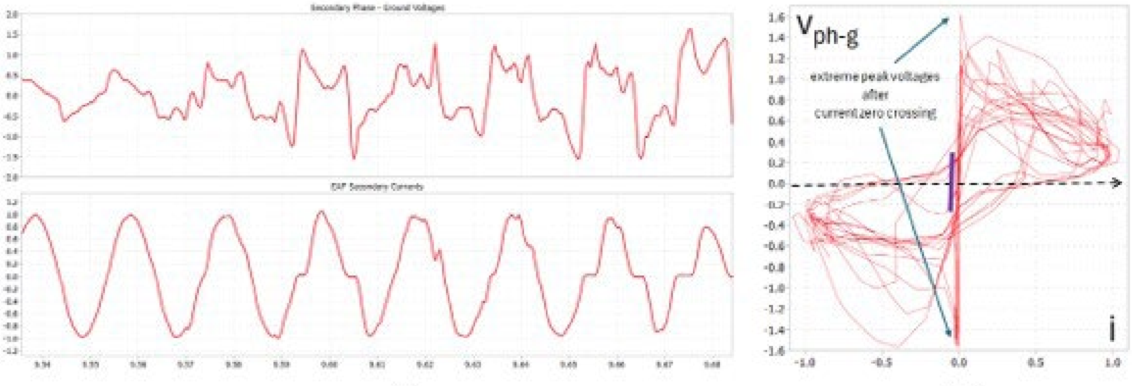
This section presents first experimental field test validation results for the proposed active zero-crossing support of EAF arc currents by means of the assisted arc ignition control (AAI control) method introduced in the previous section. The active zero-crossing support function was implemented in a Medium Voltage (MV) EAF current-controlled converter supply system and evaluated under real high-power scrap EAF operating conditions. All measurements shown in this section were taken during the same operational condition of the furnace, in switching AAI control on and off for a certain period. Prior to activation of the zero-crossing support function, arc current and voltage waveforms were recorded at the transformer secondary side (figure 10).



(a) (b)

Fig.10 - Measurement results illustrating (a) p.u. arc current i and secondary phase-ground voltage waveforms and (b) dynamic voltage = f(i) plot **without assisted arc ignition control**.
Correlations between delayed current zero crossings and high voltage peaks are clearly visible.

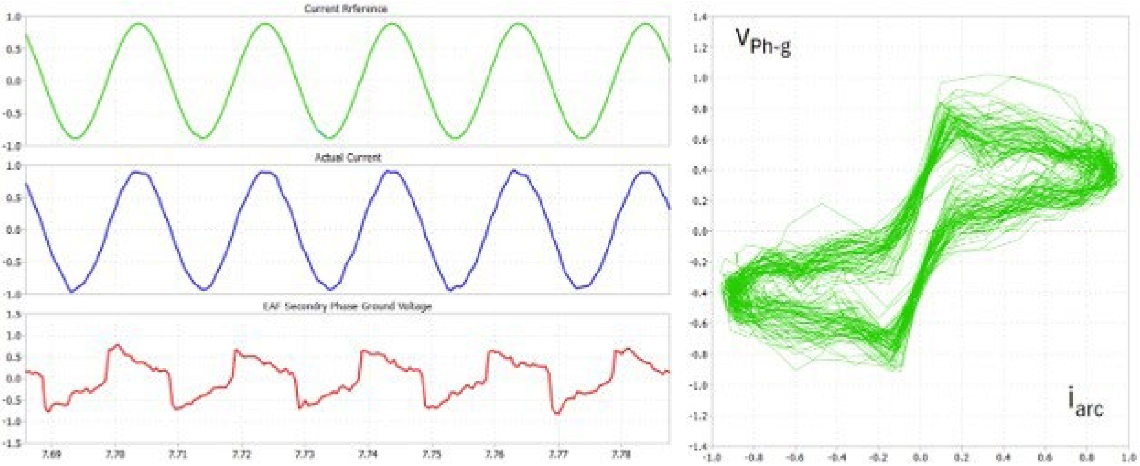
The measurements reveal delayed arc-current zero crossings associated with elevated voltage peaks. Under extreme conditions, excessive increases in arc resistance near the current zero crossing can cause the reignition-voltage peaks to escalate rapidly, potentially resulting in sustained arc instability and, ultimately, arc extinction (figure 11).



(a) (b)

Fig.11 - Measurement results showing the (a) p.u. secondary phase-to-ground voltage and arc current (i) waveforms, together with (b) the dynamic voltage characteristic v = f(i) (b), **without assisted arc ignition control**. The extreme case shown here is characterized by rapidly increasing reignition-voltage peaks resulting from successive increases in arc-current zero-crossing delays.

After the active zero-crossing support was enabled, delays in the arc current zero crossings were virtually eliminated although EAF was operating in identical operational conditions as in prior case. Consequently, the peaks in the secondary-side phase-to-ground voltages were noticeably reduced at the current zero crossings, together with the distortion of the EAF currents, as shown in figure 12.



(a) (b)

Fig.12 - Measurement results (p.u. values) illustrating (a) current reference, actual arc current i and secondary phase-ground voltage waveform and (b) dynamic voltage=f(i) plot **with assisted arc ignition control enabled**. Smoother current zero crossings and a related reduction of arc voltage peaks is clearly visible.

Note: The additional voltage pulses shown in figure 9 were injected at the current zero-crossings. Their effect is not visible in the current reference, but in the actual currents (no discontinuity at current zero-crossings).

The obtained preliminary results are in very good agreement with the simulation results presented in the previous section. Furthermore, the results demonstrate that active support of arc current zero crossing by means of the converter-based supply system is feasible under real EAF operating conditions. Additional long-term tests will be carried out to evaluate the impact of the proposed approach on the overall EAF performance.

GENERATION OF IMBALANCE AND MODULATION OF EAF CURRENTS

Due to special requirements for individual control of thermal power delivered by the electrodes, and need for spatial balancing of temperatures within the EAF, options to impose imbalanced electrode currents are desired. EAF electrode current references are typically defined by their rms values. From these values the instantaneous phase or space vector current references are derived using the space vector concept and d,q and α,β transformations. Further, as the electric arc is a plasma jet with an impulse of force creating movements in the bath, it is of interest to modulate the intensity of this force. By modulation of intensity of the 3-phase electrode currents at a relatively low frequency of 0.1-2 Hz (with appropriate phase shifts of the currents with respect to their geometric positions), a movement in the liquid bath (steering) can be generated, to enhance heat distribution in the molten bath. Thus, the current reference generator is expanded to generate individually settable imbalanced or fluctuating phase current references. Figure 13 shows examples of balanced/imbalanced and modulated balanced/imbalanced current references (space vector trajectories and phase currents).

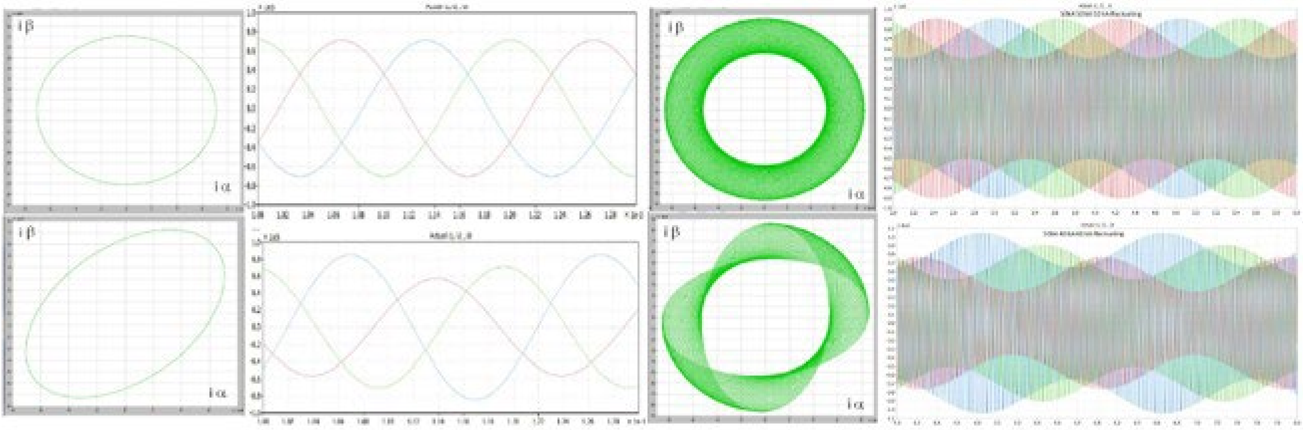


Fig.13 - Space vector trajectories of balanced and imbalanced three phase currents and fluctuating balanced and imbalanced three phase currents.

CONCLUSION

DF power supplies take the power quality of electrical arc furnaces to a new level and enable EAF operation in comparably weak grids, e.g. grids substantially powered by renewable energy sources. They also enable EAFs with nominal power and heat sizes that exceed the capacity of conventional furnaces. For very large furnaces it is key to assure arc stability not only in hot but also in a cold state of the furnace. To enable increased arc stability, new converter control algorithms have been developed that do not only enable controlling the amplitudes of the electrode currents to be constant, irrespective of the arc length, but also to avoid current interruption during electrode current zero crossing, thus enabling more stable operation in cold EAF condition.

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