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New Multi-Level Converter System for Electric Arc Furnace Applications

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ABSTRACT

A new Modular Multilevel Converter (MMC) system based on press-pack IEGT technology has been introduced by GE Power Conversion in 2020. The submodules of the new MMC system benefit from the robust press-pack technology used in more than 1000 high power drive applications. The fully modular design and a new control architecture allow high flexibility for adaptions on special customer requirements. Designs of the main MMC topologies relevant for STATCOM and Direct Feed (DF) Electric Arc Furnace (EAF) power supplies are presented in this article, together with performance results from simulations and site measurements, e.g., on reduction of flicker produced by EAFs.

Keywords: Electrical arc furnace, power quality, modular multilevel converter, flicker, direct feed converter system

INTRODUCTION

Global steel industry is currently facing challenges driven by decarbonization objectives, increasing energy prices and power quality requirements. To meet the associated process and performance objectives, GE Power Conversion has developed new modular multilevel converter (MMC) system solutions that can be scaled up to power levels above 150 MVA. These converter systems are based on robust press-pack IGBT technology that has been adapted to meet the special needs of EAF Medium Voltage (MV) power supplies. The latest of these MMC products includes a DF EAF MV power supply with a Hybrid Modular Multilevel Rectifier (HMMR) front-end. With this new topology 33 % of the IGBT submodules (SMs) of the grid converter can be replaced by simple HV line-frequency diode stacks. Part of the active power is delivered through the diodes directly, which also reduces the MMC energy storage requirement and reduces converter losses and increases converter efficiency. The fully modular design and a new control architecture allow high flexibility for adaptions to meet special customer requirements, e.g. for EAF process improvements (EAF power and voltage ranges) or high power quality requirements.

DISCUSSION

1. Power Quality Improvement Requirements and STATCOM Technology for Electric Arc Furnaces

Nonlinear loads such as Electric Arc Furnaces (EAF) are at the origin of degradation of power quality with major consequences such as harmonic pollution, voltage fluctuations and generally current and voltage unbalance. In industrial applications and especially in weak grids, voltage unbalance and voltage flicker are particularly difficult to mitigate. Flicker produced by EAFs is mainly due to reactive, and active power variations of the load. EAF power supply systems generally require a power factor corrector and balancer that provides dynamic reactive power and inverse sequence current compensations. The compensator is typically connected in parallel to the EAF load. A classic example for such compensation systems are Thyristor Controlled Reactors (TCR) and Voltage Source Converter based STATCOMs combined with passive filters. The STATCOMS systems have been designed for compensation with high bandwidth and proven to provide the required dynamic performance, an example of a 100 MVA VSC based STATCOM is shown in Fig. 1. Most commonly, STATCOMs (static compensators) are used to fulfill grid standard requirements by means of controls that have been optimized to dynamically supply reactive power to achieve the required level of flicker mitigation without having to oversize the converter dc bus capacitors.

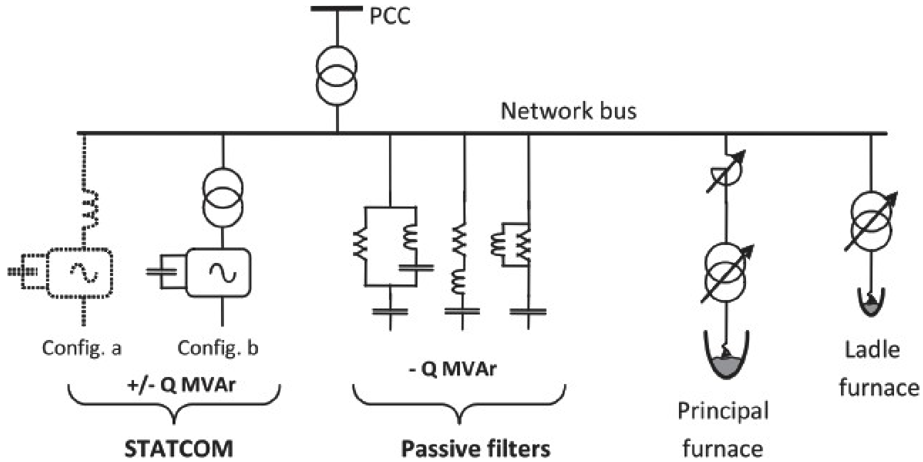


Fig. 1. Single line diagram of an EAF power supply with passive filters and a VSC based STATCOM providing dynamic active and reactive power compensation [1]

Depending on the power rating of the STATCOM and VSC, e.g., above 75 MVA - 100 MVA, a modular multilevel converter (MMC) system can provide higher operational flexibility and availability, without having to install bulky equipment like transformers as part of the STATCOM installation. Fig. 2 shows the single line diagram and Fig. 3 an example installation of a MMC based delta STATCOM for direct connection to MV grids with nominal voltages up to 30 kV AC. As the MMC converter arms are basically single-phase converters with naturally higher dc energy storage installed in the module dc links, they can provide, in addition to the reactive and imbalance current compensation, a high level of compensation to EAF active power fluctuations, which are also source of voltage flicker in weak grids and when the grid impedance X/R ratio is low (<3).

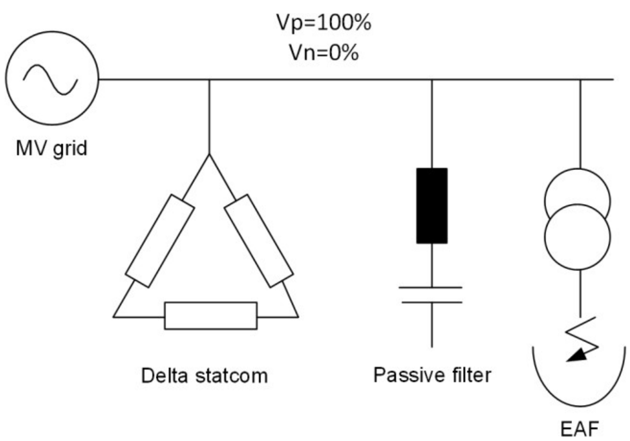


Fig. 2. Schematic of a direct MV grid connected 3-phase delta STATCOM based on MMC technology

Fig. 3. 100 MVA MMC Delta STATCOM [2]

2. Press-Pack Multilevel Converter Technology for EAF STATCOMs and Direct Feed (DF) Power Supplies

The MMC products introduced by GE Power Conversion in 2020 are based on proven and mature MV7000 VFD technology. The so-called MM7 products provide a modular approach to achieve a customized solution across different applications. MM7 is a multilevel converter, transformer-less, with remote support and grid monitoring capabilities to ensure power quality that meets all grid standard requirements. The modular MV design is based on high power cells providing increased flexibility for the installation, operational efficiency, and higher availability through the possibility to include n+1 or n+2 redundancy at individual power cell level. The power cells are based on the proven press pack IEGT technology that has been used by GE Power Conversion in MV drives for almost 20 years [3]. The single IEGTs have a 4.5 kV nominal voltage, with several current ratings available, mainly 750A, 1500A, 2000A and 3000A (trench devices). The power stacks are cooled by deionized water. Each IEGT benefits from double side cooling thanks to the press pack technology. Another benefit of press pack technology 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 cells. Two types of cells have been developed to serve the different topologies used in the MMC converter family: the half-bridge (HB) cell and the full-bridge (FB) cell, see Figs. 4 and 5.

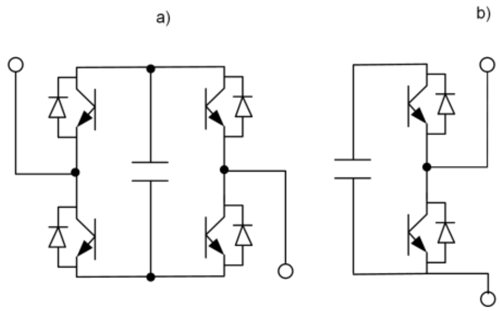


Fig. 4 Electrical schematics of FB (a) and HB (b) cells

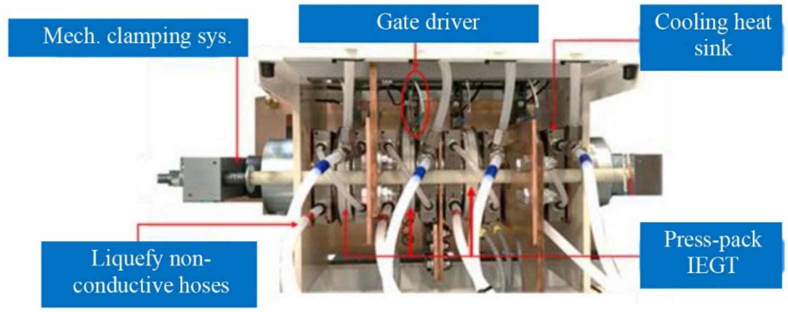


Fig. 5 Photo of one cell with 4 IEGTs

The MMC cells are assembled in a MMC building block that is manufactured and tested in the factory prior to site shipping. The building block includes several submodules (typically 3-4 in FB configuration, and 6-8 in HB configuration) connected in series, the hydraulic distribution from a grounded manifolds, a local controller, and an grounded power supply which enables full control and monitoring functions prior to valve energization. Figures 3 and 4 show state of the art examples of MMC FB and HB building blocks ("towers").

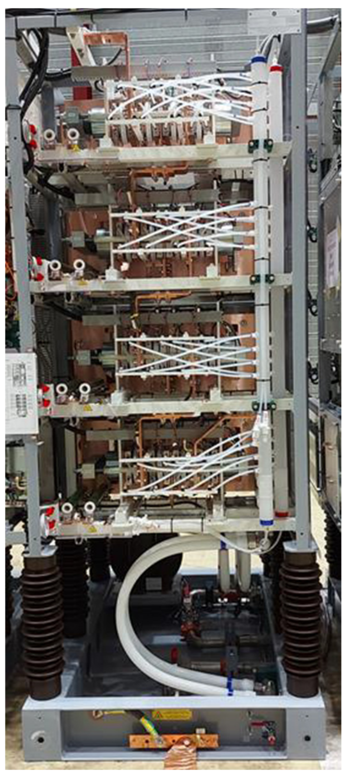


Fig. 6 MM7 FB Tower with 4 MMC cells

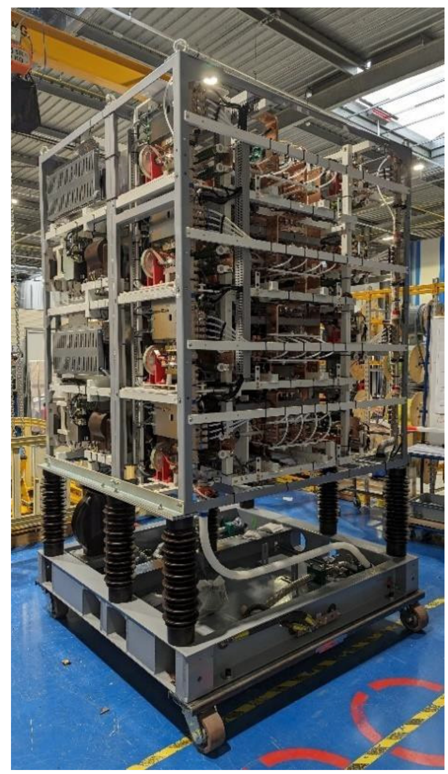


Fig. 7 MM7 HB Tower with 8 MMC cells

3. Main MM7 Power Conversion Topologies for EAF Applications

Modular multilevel converters can be used in many topologies and for several markets. This chapter explains the offer of GE Power Conversion for EAF applications and which adaptions have been made to meet the special needs of electric arc furnace power supplies.

3.1 STATCOM Topology

The connection of full bridge modules in series to enable transformer-less connection of a STATCOM to a MV grid is widely used. The GE Power Conversion offer focuses on two main markets:

- Single phase STATCOM, also known as High Voltage Booster (HVB), for rail voltage distribution
- Three phase delta STATCOM, focused on EAF market and with a real-time control architecture that enables to reach a mitigation ratio of the flicker up to the factor of six [2]

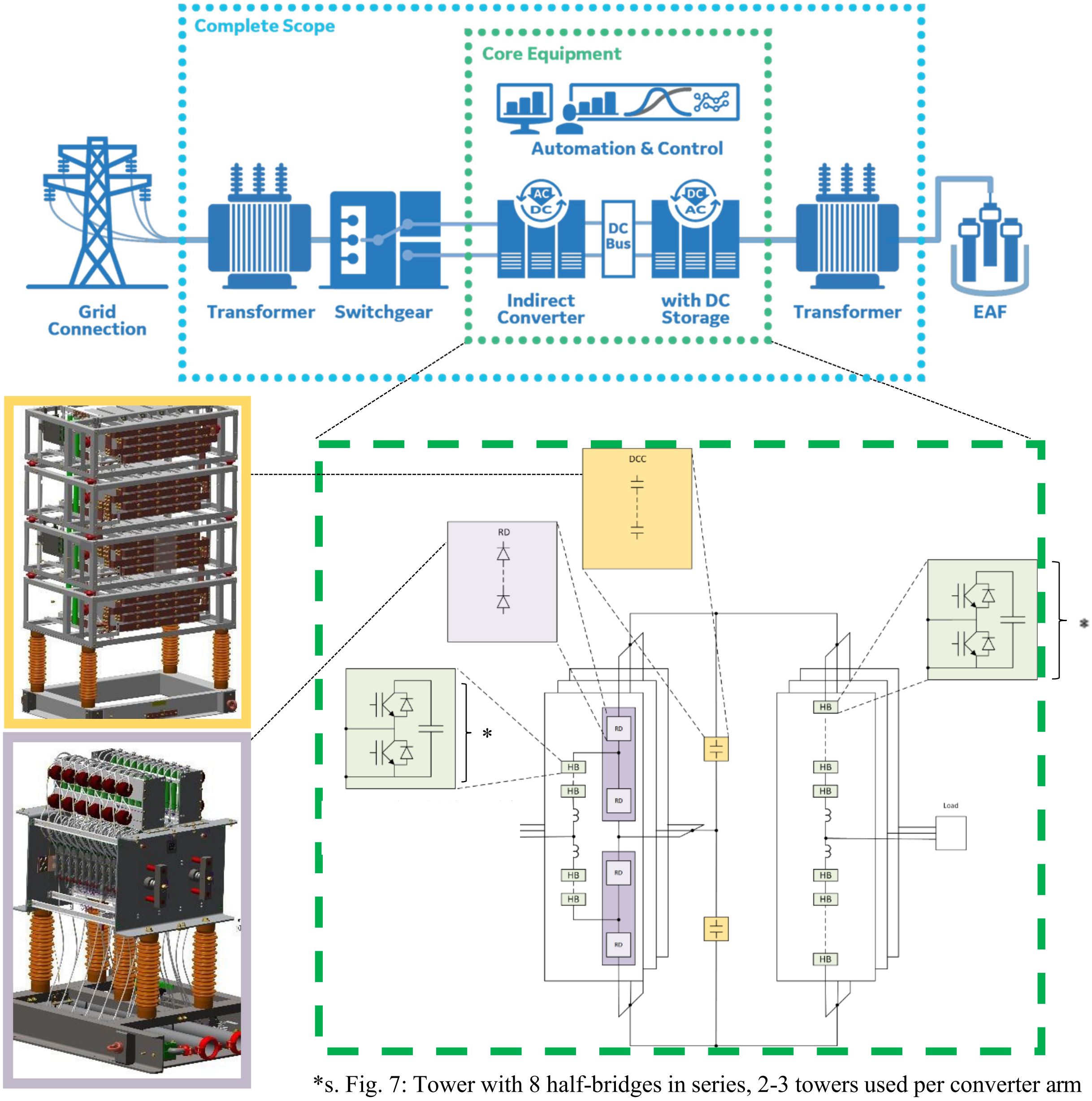
Such EAF STATCOM may use an amount of passive filters compensation in addition to the dynamic compensation of the STATCOM valves. The STATCOM must compensate for the filter at no-load operation, therefore the ratio of STATCOM compensation power divided by the passive filter power can vary from 50%/50% to 100% / 0% (no passive filter compensation). An example of a 3-phase delta STATCOM system with fully unbalanced currents and fully balanced voltages is shown in Figs. 2 and 3.

3.2 Double star AC and Hybrid MMC (HMMC) Topology for Direct Feed EAF Supply

MMC technology also enables to directly feed a two or three phase EAF. The MMC system decouples the number of phases, the dynamic load and the operating frequency of the arc furnace from the 50 or 60 Hz mains system, as shown in Fig. 8. This provides the following advantages in comparison to classical EAF power supplies [4] – [6]:

- Controlled EAF currents, more stable EAF operation and increased active power throughput
- Reduced electrode consumption
- EAF to generate lower flicker and harmonics
- Reduced stress and losses on entire power supply network
- Separate compensation systems and harmonic filters no longer required
- Modular design of EAF Direct Feed converter with built-in redundancies to enable maximum availability
- Direct MV grid connected design of EAF converter, does not have to be installed in furnace building
- Possibility to re-use existing EAF transformer (no special converter transformer required)
- Possibility to control voltage and frequency of EAF supply, reducing control requirement for transf. tap changer

In addition, reactive, and also active power variations of the EAF load can be directly compensated and additional converter control functions can be implemented that help to provide advanced EAF process control. The drawback of a direct feed EAF power supply is that it requires a power conversion system with comparably high nominal power, robustness, and availability. MV MMC topologies would be best suited to provide an EAF direct feed power supply because of their modular structure, excellent power quality, and fault-tolerant operation capability. But the classical Double Star (DS) back-to-back MMC converter topologies (used in HVDC applications) require to install a comparably high number of actively switched and controlled power cells and cell capacitors, which typically occupy more than 50% of the weight and size of MMC [7]. Given that the power flow of EAF power supply systems is unidirectional only, GE Power Conversion has introduced a hybrid multilevel converter system. This so-called Hybrid Modular Multilevel Rectifier Type 1 (HMMR1) topology, shown in Fig. 8, enables to significantly reduce the volume, weight, efficiency, and cost for double-star (DS) power conversion systems [8]. It is basically a combination of classical three phase 6-pulse rectifier enhanced by the ac and dc current shaping circuitry which is composed of chain links of half bridge modules (arms) like in classical DS MMC star converters. However, the HMMR1 (operated at unity power factor) requires only half of the modules needed in DS MMC converters. In a direct feed EAF power supply the grid side converter will be run in nonunity power factor operation to deliver some amount of reactive power and support the grid during the low-voltage transient and weak grid conditions. In this setup still one third of the chain links of half bridge modules can be replaced by simple diode stacks as shown in Fig. 8 (RD). The DC link capacitor banks (DCC) provide additional energy storage and de-coupling between the EAF load and the grid.



*s. Fig. 7: Tower with 8 half-bridges in series, 2-3 towers used per converter arm

Fig. 8. Topology and main equipment of Hybrid MMC converter system for direct feed EAF supply. Each of the diode stacks ("RD") replaces 8 MMC half-bridges. The DC link cap. banks ("DCC") provide additional electric energy storage.

3.3 Control and Performance of Multilevel Converters for Electric Arc Furnace Power Supplies

3.3.1 EAF Control Challenges

The mitigation of arc furnace perturbations provides an extreme load scenario for MV equipment. The main control task challenge is to compensate arc furnace impact on the grid during electric arc heating, including the reduction of flicker effects. As illustrated in Fig. 9, the currents from the arc furnace during a heat cycle are very unpredictable (erratic, asymmetric, fast variation…). To be able to actively compensate this type of waveform with the right level of efficiency, one of the key points is to have a control with fast response behavior. In previous STATCOM projects, the sampling period of the current loop has been chosen to be about 40µs on the installed MM7 equipment [2]. In Fig. 9, there are not only three but six curves visible: Three current reference values provided by the control system and three measured currents that follow the current references in real time (see zoomed window). They represent the measured three-phase currents of the delta STATCOM, required to actively mitigate the EAF perturbations.

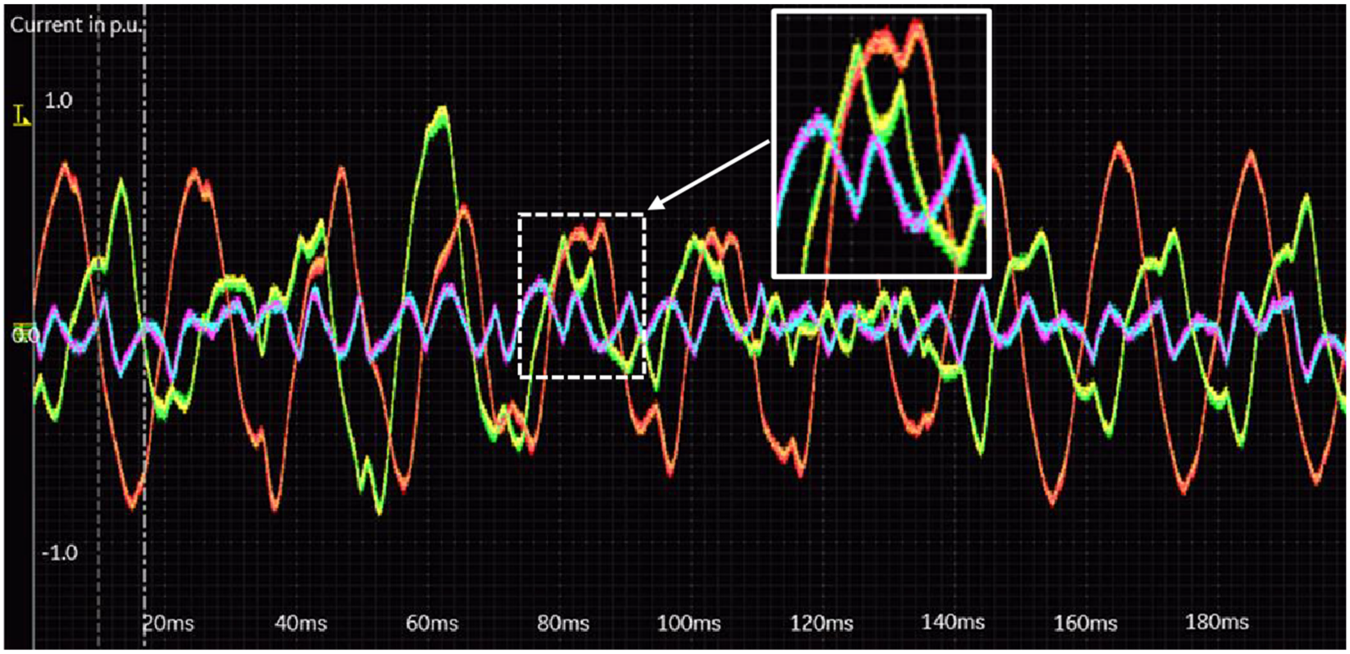


Fig. 9 Current reference waveforms and measured phase currents of a 125 MVA MM7 converter system

3.3.2 Direct HMMC power supply for advanced EAF power quality and process control

The potential advantages of a direct converter fed EAF power supply have been studied by the detailed simulation model shown in Fig. 10, which includes the power conversion system with all equipment of Fig. 8 and a control system with basically the same dynamic performance as the one used in previous MM7 STATCOM projects.

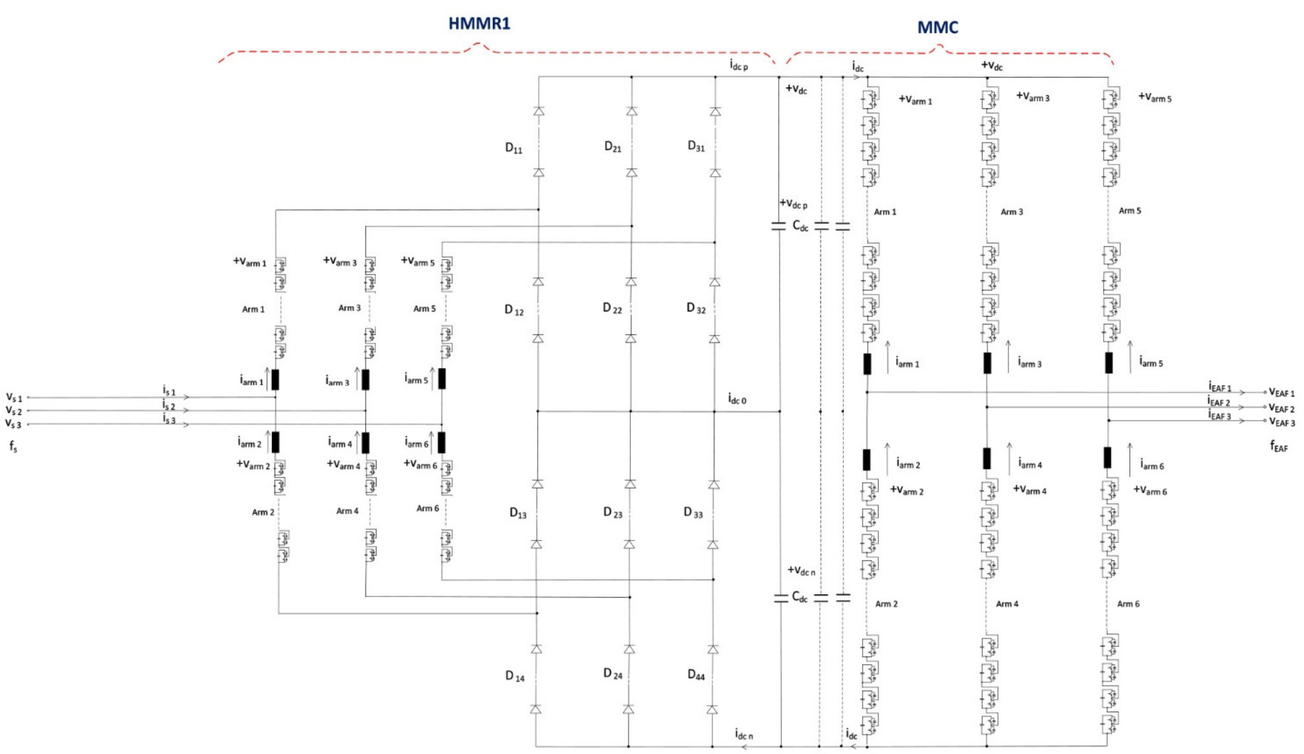


Fig. 10 Hybrid ac/dc/ac converter composed of HMMR1 rectifier (ac/dc) stage at the grid side and MMC inverter stage at the EAF side.

The simulation results show that the HMMC power converter effectively limits the EAF short circuit current peaks, reduces the number of instances when arcs are interrupted, and improves EAF current stability and efficiency of the power conversion process. It also effectively decouples the EAF from the grid. Thus, there are neither the reactive current or current imbalance injections at the power grid/supply side. Only slow EAF active power variations caused by arc length/voltage perturbations are transferred to the grid side. The EAF active power variations are significantly mitigated at the grid side by the MMC and HMMR converters thanks to their respective energy storages. Optionally, the back-to-back converter energy storage can be increased by adding more capacitor banks ("DCC") into the DC link. This allows to achieve flicker mitigation factors which are far above those achievable by any shunt compensation system. This is important, particularly when the grid short circuit power is relatively low compared to the EAF power, where grid quality factors (X/R) are low and when flicker limits allowed by the grid operator are low. Source side currents are 3-phase balanced and purely active (in phase with the corresponding supply side voltages). Magnitudes are adjusted to control average power absorption which mirrors the EAF total power demand. These simulation results are illustrated in Figs 11 – 13.

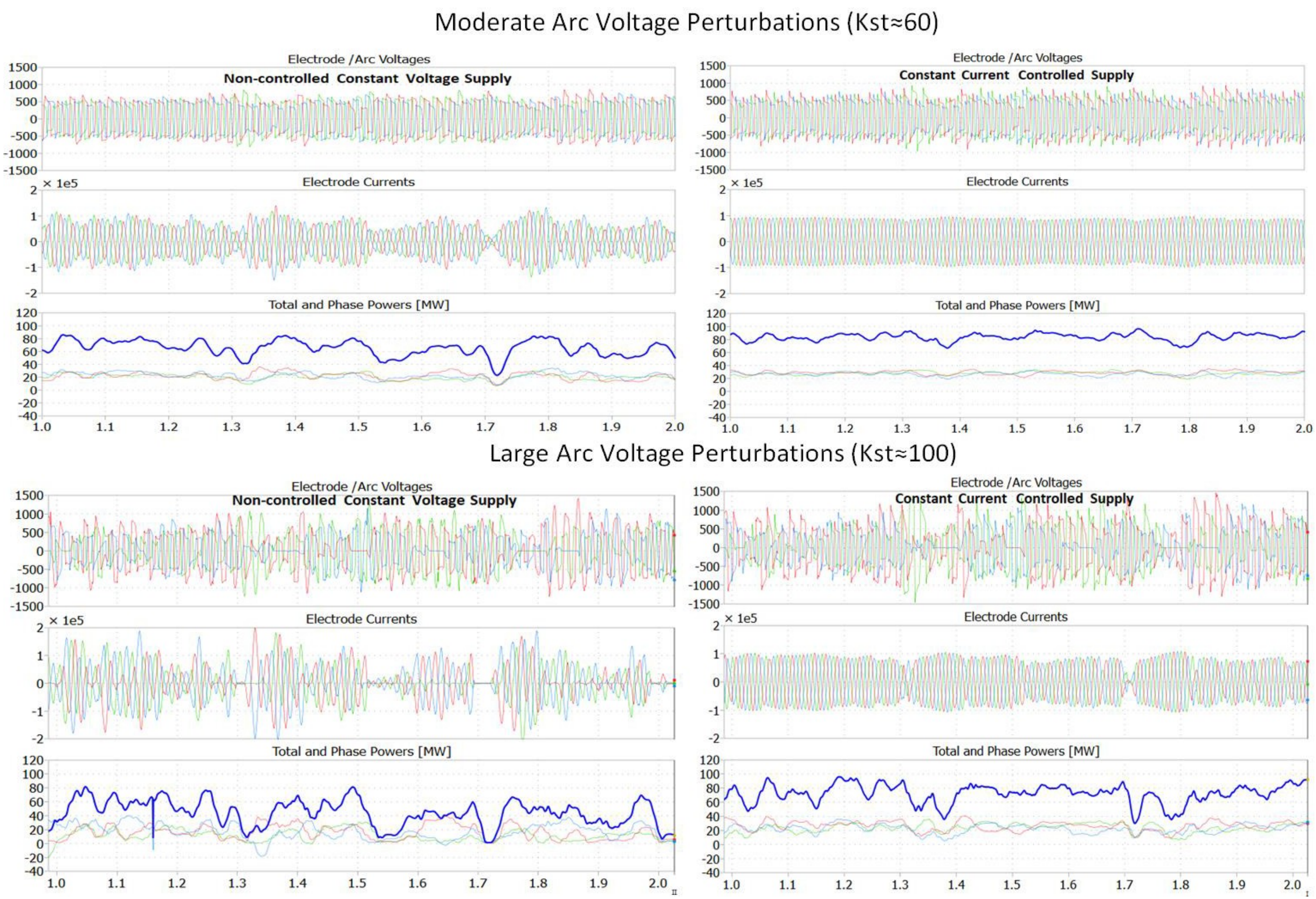


Fig. 11 Simulation results illustrating differences in the EAF currents and powers with the classical voltage and controlled current supplies in two situations with moderate and large arc voltages perturbations.

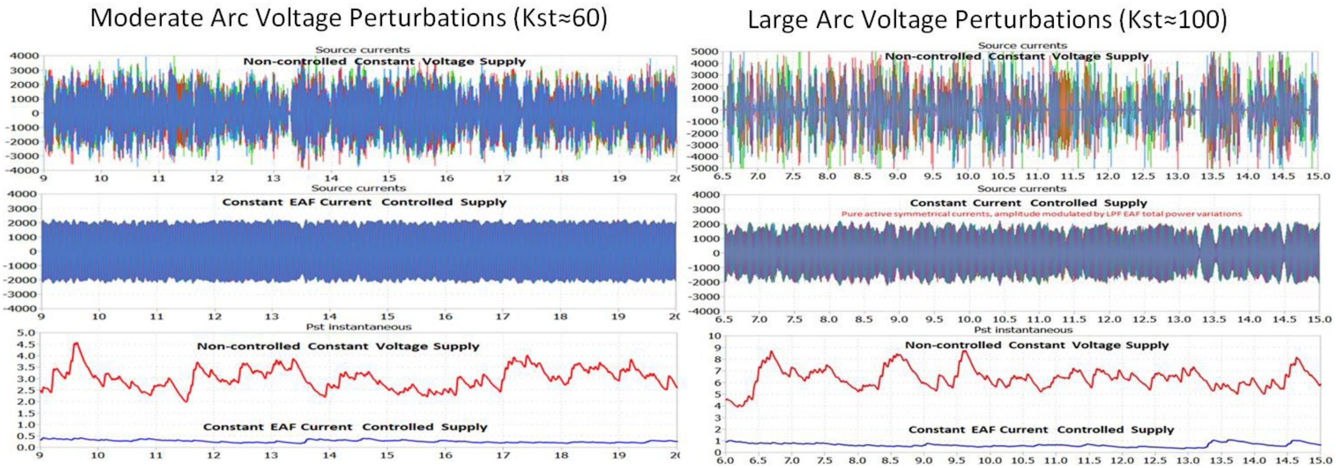


Fig. 12 Simulation results illustrating power grid current and instantaneous flicker with the classical voltage and controlled current supplies in two situations with moderate and large arc voltages perturbations.

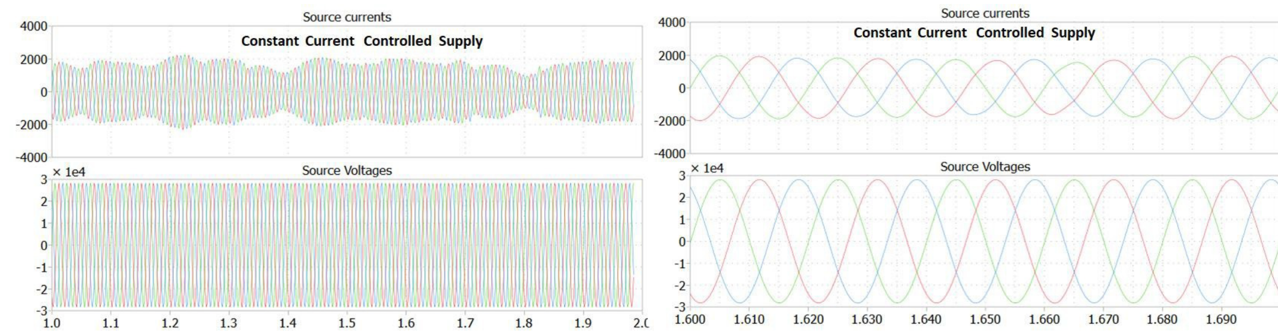


Fig. 13 Enlarged view of the grid side current and voltage waveforms.

The following simulation results illustrate an increase in the rate of the energy transfer from the grid to the EAF when switching from the standard voltage controlled supply to a current controlled supply.

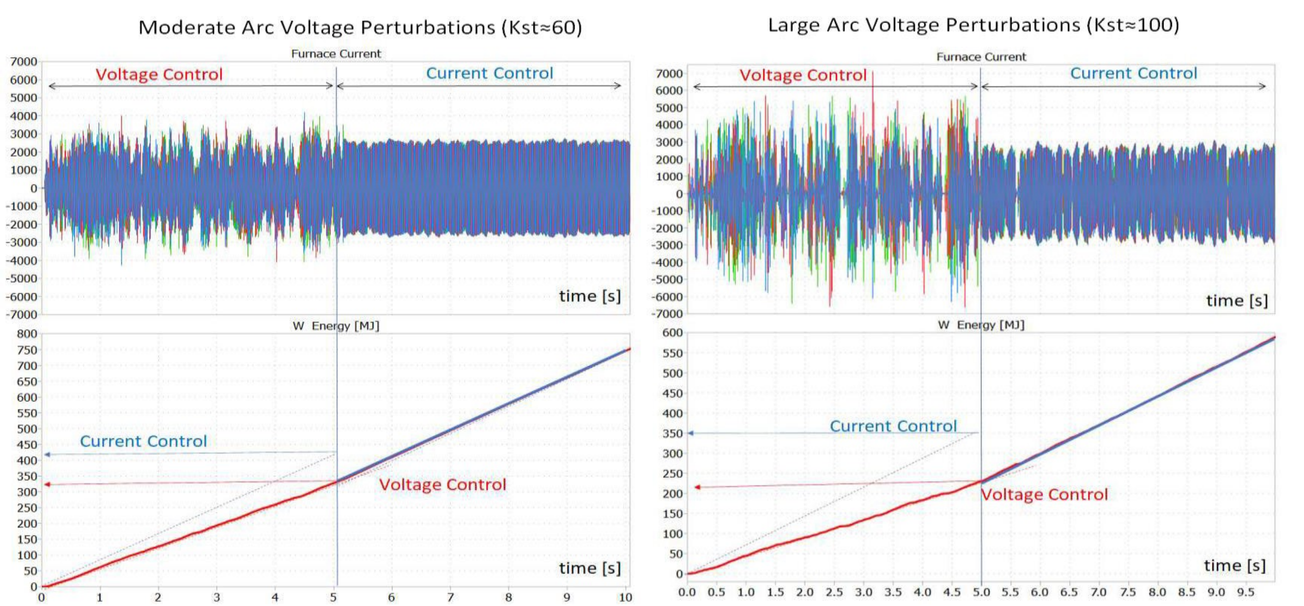


Fig. 14 Illustration of changes of rates of energy transfers when switching from the EAF classical voltage controlled supply to an EAF current controlled supply, enabled by the conversion system shown in Figs. 8 and 10

CONCLUSIONS

Conventional EAF power supply and compensation methods have been discussed in this paper, including known challenges and limitations. To overcome these problems and also provide a path forward to new challenges driven by energy efficiency, decarbonization and increasing power quality requirement, a new direct converter fed EAF power supply solution has been developed. It is based on a robust technology associated to an industrial modular power electronic building block. It can provide the same very fast response time and control performance as a classical MMC converter system but requires less actively switched power cells and capacitors. It enables a current controlled supply of the EAF with higher rates of energy transfer and less power quality issues than achievable with a standard voltage controlled supply. The expected benefits include more stable EAF operation, reduced electrode consumption, the possibility to control the voltage and frequency of the EAF supply, no need for separate compensation systems or harmonic filters, and reduced dynamics on the entire power supply network and equipment.

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