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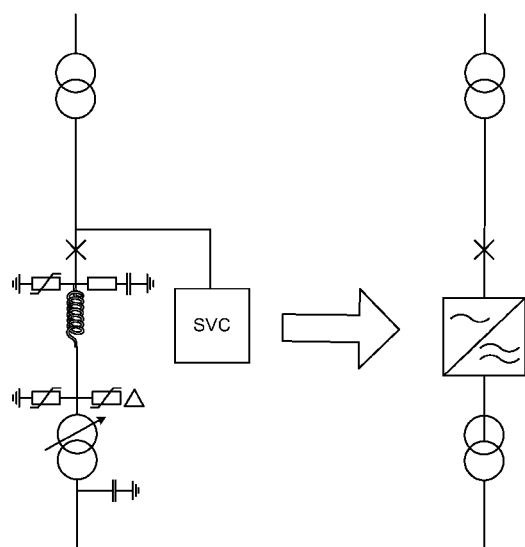
(54) Title: A METHOD FOR OPERATING AN ELECTRIC-ARC FURNACE, A POWER ELECTRONIC CONVERTER, AND AN
ELECTRIC-ARC FURNACE SYSTEM

Fig. 1

(57) Abstract: The present invention relates to a method for op-
erating an electric-arc furnace, EAF. The method comprises con-
verting, in a power electronic converter, a grid frequency to an op-
erating frequency for an EAF, controlling, in the power electronic
converter, the converted operating frequency between 100Hz and
1 kHz, and operating one of more electrical arc(s) of the EAF with
the controlled converted operating frequency. Corresponding pow-
er electronic converter, EAF system and power transformer are also
presented.

A METHOD FOR OPERATING AN ELECTRIC-ARC FURNACE, A POWER ELECTRONIC CONVERTER, AND AN ELECTRIC-ARC FURNACE SYSTEM

TECHNICAL FIELD

- 5 The invention relates to a method for operating an electric-arc furnace, a power electronic converter for operating an electric-arc furnace, and an electric-arc furnace system.

BACKGROUND

- The electrical power supply for electric arc-furnaces (EAFs) used for melting
10 scrap steel consumes a lot of power, in the order of 100 MW. The electrical power consumption cost and the other operation costs, like electrodes, are crucial for steel plant owners. The speed of the melting process is also crucial since a higher speed enables more steel produced per heat. Improving the melting process in order to improve the efficiency of the process is thus of
15 great interest. Improving reliability and availability of EAF supply system is of great interest for industry.

SUMMARY

An object of the invention is to enable improved reliability and availability for electric-arc furnaces (EAFs).

- 20 According to a first aspect, there is presented a method for operating an electric-arc furnace, EAF. The method comprises converting, in a power electronic converter, a grid frequency to an operating frequency for an EAF, controlling, in the power electronic converter, the converted operating frequency between 100 Hz and 1 kHz, and operating one of more electrical
25 arc(s) of the EAF with the controlled converted operating frequency. The power electronic converter may be of a voltage and/or a current source type.

By the first aspect, reliability and availability for EAFs are improved by increased productivity and efficiency, and by reduced electrode consumption and minimized refractory wear out.

The EAF may comprise more than one electrode, and the power of each electric arc is controlled individually.

The power of each electric arc may be controlled individually by individually controlling voltage, current and frequency. The power of each electric arc
5 may be controlled individually by individually controlling voltage and current magnitudes and phase angles.

The EAF may be operated with a power of at least 50 MW, preferably about 100 MW, optionally for melting metal scrap.

The power electronic converter may comprise a rectifier connected to one or
10 more inverters.

The EAF may comprise three or more electric electrodes.

The EAF may comprise at least four electric electrodes and the electric arcs are controlled separately in groups.

The converted operating frequency may during melting be controlled
15 between 100 Hz and 1 kHz.

According to a second aspect, there is presented a power electronic converter for operating an EAF. The power electronic converter comprises an inverter configured to convert a grid frequency to an operating frequency for an EAF, to control the converted operating frequency between 100 Hz and 1 kHz, and
20 configured to operate one of more electrical arc(s) of the EAF with the controlled converted operating frequency.

The converted operating frequency may be controlled between 100 Hz and 1 kHz for melting.

The inverter may be configured to control the converted operating frequency
25 between 100 Hz and 1 kHz individually for more than one electric arc of the EAF.

The power electronic converter may be a matrix converter.

The power electronic converter may comprise a thyristor rectifier, and the inverter may be a Modular Multi-Level Converter (MMC).

The power electronic converter may comprise a diode rectifier, and the inverter may be an MMC.

- 5 The power electronic converter may comprise an MMC operated as a rectifier, and the inverter may be a 2L or a 3L inverter.

The power electronic converter may comprise a rectifier providing power to at least two inverters arranged in parallel. The at least two inverters may be connected to a common three-phase EAF transformer. The at least two
10 inverters may be connected to separate three-phase EAF transformers, which in turn may be connected in parallel to supply three EAF electrodes.

The power electronic converter may comprise a rectifier providing power to at least three inverters arranged in parallel. The at least three inverters may be connected to separated one-phase EAF transformers, which in turn may
15 separately be connected to three EAF electrodes. The power electronic converter may comprise at least six inverters that are connected to separate one-phase EAF transformers, which in turn may be paired together in parallel and supply three EAF electrodes.

The one-phase EAF transformers may be connected to the EAF electrodes in
20 series instead of in parallel.

The power electronic converter may comprise a rectifier providing power to six inverters arranged in parallel, wherein each primary winding of a three-phase EAF transformer may be connected to two of the inverters. The power electronic converter may comprise a DC-link between the rectifier and the six
25 inverters, which DC-link has three bus-bars.

The power electronic converter may comprise a rectifier providing power to at least two inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, each in turn connected to at least two EAF electrodes.

The power electronic converter may comprise a rectifier providing power to at least four inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, which are grouped in pairs, and which pairs each in turn are connected to at least two EAF electrodes.

- 5 The power electronic converter may comprise a rectifier providing power to at least six inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, which are grouped in threes, and which group each in turn are connected to at least three EAF electrodes.

- 10 The power electronic converter may comprise a rectifier, and at least two inverters connected in series to the rectifier and in parallel to an EAF transformer. The inverters may be isolated galvanically between input and output.

- 15 The power electronic converter may comprise a rectifier, and at least three inverters connected in series to the rectifier and in parallel to multiple primary windings on an EAF transformer.

The power electronic converter may comprise a current source rectifier, and wherein the inverter may be a current source inverter.

The power electronic converter may comprise a rectifier, the rectifier being a single unit or several units in parallel or in series.

- 20 According to a third aspect, there is presented an EAF system. The EAF system comprises a power electronic converter, one or more EAF transformer(s), and an EAF.

- 25 According to a fourth aspect, there is presented a power transformer for supplying an EAF with power at frequencies between 100 Hz and 1 kHz. The power transformer is configured to supply power to one or more electrical arc(s) of the EAF with the operating frequencies.

Generally, all terms used in the claims are to be interpreted according to their ordinary meaning in the technical field, unless explicitly defined otherwise

herein. All references to "a/an/the element, apparatus, component, means, step, etc." are to be interpreted openly as referring to at least one instance of the element, apparatus, component, means, step, etc., unless explicitly stated otherwise. The steps of any method disclosed herein do not have to be
5 performed in the exact order disclosed, unless explicitly stated.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is now described, by way of example, with reference to the accompanying drawings, in which:

Fig. 1 schematically illustrates differences between prior solutions compared
10 to an embodiment of the present invention;

Fig. 2 shows diagrams schematically illustrating differences between three phases in an EAF; and

Figs. 3-17 schematically illustrate different topologies of embodiments of the present invention presented herein.

15 DETAILED DESCRIPTION

The invention will now be described more fully hereinafter with reference to the accompanying drawings, in which certain embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth
20 herein; rather, these embodiments are provided by way of example so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout the description.

Electric-arc furnaces (EAFs) are today operated by the available power
25 system using the line frequency of either 50 Hz or 60 Hz. The used sinusoidal voltages with 50 Hz or 60 Hz are however not optimal for maintaining stable arcs in EAFs.

Electrical power supply for EAFs including a voltage source converter or current source converter with or without a medium frequency EAF transformer, utilizing a variable frequency converter system, for power supply for control of a melting process is presented.

- 5 Improvement of the process like the speed of the melting process and saving energy is very important with respect to cost. The productivity, efficiency, reduced electrode consumption and minimize refractory wear out are improved when being operating at higher and variable frequency and by balancing the currents in the phases.
- 10 The steel production rate is also very important, which is influenced both by the production rate in the EAF and by planned and required maintenance and also unplanned outages due to repair work of the electric system supplying electric power to the EAF.

- 15 The use of a variable and high frequency for the EAF power supply, utilizing a power electronic converter, is presented. It will improve the production rate in the EAF when operated at higher frequencies than the standard 50/60 Hz. The power electronic converter enables both the frequency and the voltage to be varied during the melting process in an EAF, which opens up for an improved melting process.

- 20 Differences between an electric system supplying power to an EAF today and the presented solution are illustrated in Fig. 1. Shunt connected static var compensator and filters are replaced by a variable frequency converter, which is located between an EAF and the power grid. This changes the requirements on most of the electrical power products. An EAF transformer may be
- 25 configured for operation at about 500 Hz and maintenance requirements of On-Load Tap Changers (OLTCs) can be excluded since the voltage control is instead performed by the variable frequency converter.

- There is today further only one three-phase transformer per EAF, but the use of having one converter and transformer per phase enabling individual
- 30 control of the arc power for each phase is also presented. The converters and

transformer may be built of parallel modules each containing one converter and one transformer. When utilizing parallel building blocks also an option of different frequencies for the different blocks may be applied.

By the present invention, the production rate of EAFs is improved and the energy consumption is reduced. It is thus possible to produce more iron at lower energy costs by stabilizing the arcs and injecting more active power into the arcs, due to that the converter transfer rate of thermal energy to the scrap is higher and a balanced current can be provided and more stable arcs can be secured.

Process analysis of EAF scrap melting can be used to optimize the power frequency and power stability for melting periods and refining period, respectively.

A test has been performed to identify three different phases in a three-phase EAF, which is illustrated in Fig. 2. From Fig. 2 it is evident that the three phases act very different from each other, and would benefit from individual control. The current amplitude differs in the three phases 1-3. The power factors differ for the three phases, and the phase angle between the voltage and current also differs for the three phases. A delay exist after a current zero crossing before the arc is re-ignited. The currents are not completely sinusoidal.

By adding a variable frequency converter system feeding the EAF transformer, improved efficiency of the EAF is achieved, when operating at higher frequencies. Further, variable frequency and voltage during the melting process provides for that a more stable arc can be maintained. By having a variable frequency converter system, an EAF transformer can have a reduced size for the same power when the fundamental frequency of the current is increased, and further, on-load tap changers can be omitted which saves cost and need of frequent maintenance.

Series reactors for stabilizing the arcs can be made smaller. Over voltage protection against vacuum circuit breaker transient over-voltages are no

longer needed. A standard vacuum circuit breaker can be utilized replacing high duty EAF vacuum circuit breakers.

Experiments with a wide range of frequencies for tungsten inert gas (TIG) welding show that the arc stability and welding bead profile are very good or
5 excellent with frequencies from 500 Hz to 1000 Hz. The operating frequency is dependent on the electric system and EAF that are used. The operating frequency is increased above the grid frequency in order to increase di/dt during current zero crossings, and may be somewhere between 100 and 1000 Hz. Higher frequencies will reduce the cooling effect at current zero crossings
10 and frequencies over 1000 Hz will not gain any process benefits. The frequency range, 100-1000 Hz, can be further optimized according to individual electric system design and power range of EAF. Furthermore, electrode consumption will be reduced with a more stable arc. Also the power quality of the supplying network during EAF operation is improved. Faster
15 control of arc voltage and current is also achieved due to the high frequency operation.

High frequency welding provides good penetration and increases welding travel speed up to 40 %, thus with improve productivity. Compared to conventional welding machines, high frequency machines add about 25 %
20 more heat into the work in the same amount of time. A welding time reduction of 25 % was reported in a case study using Dynasty 200 DX welder with an inverter to adjust the frequency up to 250 Hz.

High frequency, over 60 Hz, causes the current to change direction more often and results in a stable arc by maintaining high and uniform
25 conductivity of the plasma with complex steel scrap during melting. Further, graphite electrode consumption is reduced, arc stability during scrap melting is increased, which reduce power consumption, inrush currents are reduced, disturbances in power system and flicker due to stable and regulated arc are reduced, tap-to-tap time is reduced, it is possible to use hollow electrodes to
30 feed in scrap in the middle during melting, and it is possible to use less reactive power.

Fig. 3 schematically illustrates an embodiment using a matrix converter for the power electronic convert, which in this case do not have a DC-link. The EAF is connected to the power grid through the power electronic converter and a three-phase EAF transformer.

- 5 A Modular Multi-Level Converter (MMC) cell structure may be used for the power electronic converter.

An option is to use reactive power compensation in one or on both sides of matrix converter.

- 10 Fig. 4 schematically illustrates an embodiment using a thyristor rectifier to rectify the power and using a regular MMC inverter. The thyristor rectifier needs harmonic filtering and reactive power compensation. This can be done by a passive filter and a reactive power compensation utilizing STATCOM or SVC or passive filters.

- 15 Compared to the embodiment illustrated in Fig. 3, more components (passive) are required on the grid side and in the DC-link.

Fig. 5 schematically illustrates an embodiment using a diode rectifier to rectify the power and using a regular MMC inverter. The diode rectifier needs harmonic filtering. This can be done by a passive filter or with a shunt connected STATCOM.

- 20 To stabilize the voltage, reactive power compensation can be implemented by using SVC or STATCOM or passive filters.

An energizing resistor may be used on the MV grid (between diode rectifier and grid transformer) to limit possible in-rush currents.

- 25 Reactive power compensation may also be added between the converter and the EAF transformer.

Compared to the embodiment illustrated in Fig. 3, more components (passive) are required on the grid side and in the DC-link.

Fig. 6 schematically illustrates an embodiment using a fundamental switched 2-level (2L) or 3-level (3L) inverter to generate voltage square waves (or quasi square waves). The MMC rectifier uses full-bridges to control the voltage level of the DC-link to the rectifier in order to control the EAF voltage level.

A filter, such as a voltage source converter (VSC), may be used between the inverter and the EAF transformer in order to smooth a steep voltage wave form.

The EAF transformer may be insulated due to a steep voltage wave form.

Fig. 7 schematically illustrates an embodiment using an EAF with two primary three-phase windings, each connected to an inverter.

The rectifier may be a line-commutated diode- or thyristor-converter or a 2L- or 3L-voltage source converter or a MMC.

The rectifier may be an MMC with full bridge converter cells to control the DC-link voltage. Thus, a fundamental switched inverter (2-level or 3-level type) configuration can be used resulting in a variable frequency and amplitude.

With the two inverters arranged in parallel, the voltage wave forms affecting the EAF transformer may be optimized to reduce total system cost.

Fig. 8 schematically illustrates an embodiment similar to that illustrated in Fig. 7, but configured with two smaller EAF transformers, which are easier to design for high variable frequencies. I.e. one larger transformer is divided into smaller three-phase transformers that are connected in parallel.

Fig. 9 schematically illustrates an embodiment similar to that illustrated in Fig. 7, but configured with three single-phase transformers, which are easier to design for high variable frequencies. I.e. one larger transformer is divided into smaller one-phase transformers.

Fig. 10 schematically illustrates an embodiment similar to those illustrated in Figs. 7-9, but configured with six single-phase transformers, connected two-and-two in parallel per phase and EAF.

Fig. 11 schematically illustrates an embodiment similar to that illustrated in Fig. 7, but configured with smaller single-phase transformers that are
5 connected in series as illustrated in Fig. 11. Two or more transformers can be connected in series for each phase of the EAF.

Fig. 12 schematically illustrates an embodiment similar to that illustrated in Fig. 7, but each of the three-phase primary windings of the EAF transformer
10 is connected to two inverters. The DC-link has three bus-bars (positive, negative and neutral voltage)

The two inverters for each winding are connected to the bus-bar as shown in Fig. 12.

Fig. 13 schematically illustrates an embodiment with two independent
15 inverters that are each connected to a single-phase EAF transformer, which in turn is connected to two electrodes in the EAF.

With two independent voltage feeders, the voltage amplitude and frequency may be change independently.

The rectifier and inverter system may be configured according to the previous
20 embodiments described above.

Fig. 14 schematically illustrates an embodiment similar to that illustrated in Fig. 13 with two independent voltage feeders that are used to change the voltage amplitude and frequency independently.

The configuration comprises two or more parallel connected inverters and
25 EAF transformers connected to a pair of EAF electrodes.

The power through each transformer will be reduced, due to parallel connection.

Fig. 15 schematically illustrates an embodiment with two independent three-phase voltage feeders that are used to change the three-phase voltage amplitude and frequency.

The configuration comprises two separate three-phase units, each feeding
5 power to three EAF electrodes through single-phase transformers.

The rectifier and inverter system may be configured according to the previous embodiments described above.

Fig. 16 schematically illustrates an embodiment with current source
converters (CSC). The CSC has typically a current stiff DC-link current. The
10 converter may be a monolithic 2L or 3L converter or a modular converter
being the dual of the MMC. In case a modular CSC is used, converter cells
may be paralleled to increase the required current rating, possibly as an
option the EAF transformer can be omitted. For the CSC, the DC-link has an
inductor and the converters direct the DC-link current to the AC phases.

15 Fig. 17 schematically illustrates two variants of an embodiment with a
number of inverters that are connected in series towards the DC-link to a
rectifier, and the inverters are connected in parallel on the EAF side.

The inverters that are connected in series are in one variant isolated
galvanically between input and output. An alternative to galvanic isolation is
20 according to another variant to have multiple primary three-phase windings
on the EAF transformer.

The rectifier can be one unit or several units in parallel or in series.

The EAF transformer may be operated up to a frequency in the range of 100
Hz - 1 kHz, and may have following features to mitigate problems associated
25 with the high frequencies (electromagnetic losses, in the conductor and core,
hotspot temperature, required mechanical strength of the winding during
continuous SC stress):

- Magnetic circuit: Amorphous and nano-crystalline materials, with Iron Nitride based material. Nano-crystalline material and Iron Nitride material support variable frequency operation. GO material with dimension designed to avoid saturation at higher frequency. The core may be toroidal, stacked or wound.
5
 - Windings: Continuously transposed thin copper strands or Litz-wire. The mechanical strength of such a conductor can be enhanced by epoxy glue or be reinforcement by steel reinforced or by strong fibre composites e.g. carbon fibre or the winding conductor may be shielded magnetically to keep the winding strand thick while reducing the eddy loss as in WO2012136754.
10 Primary and secondary windings may be parallel (however with different number of turns) without distance between them to remove leakage inductance in the transformer. To reduce short circuit inductance inter wound windings may be used, or long and thin transformer structures as in
15 US200316076 and WO1997045847 may be used.
 - Insulation system: Conventional oil and paper insulation or natural/synthetic esters impregnated high temperature insulation such as Nomex/Durabil or any other suitable insulation with enhanced partial discharge resistant properties using nano fillers.
 - 20 - Thermal management and hot spot mitigation: Active management of hot spot by heat pipe. The conductor can have in-built cooling channel, as in a water-cooled hydro-generator.
 - Type of transformer and connection: A shell type transformer may be used to keep the impedance under control. Interleaving of HV and LV winding
25 (both in shell type and core type transformer) may be used. There may be several single phase transformer or three-phase transformers. The transformer may have several modular units to optimize at the system level performance of EAF system.
- Also, a low inductance cable between the EAF transformer and the EAF is
30 desirable, due to the use of higher frequencies.

The power electronic converter may be a so-called back-to-back type of connection or a matrix converter. In case of a back-to-back the rectifier may be a thyristor converter or a diode bridge. The inverter may be a MMC, 2-level, 3-level or other type of inverter.

- 5 Inverters may be paralleled and connected to single phase transformers, which makes the design of the transformers easier for medium frequency applications. The inverter on the EAF side may alternatively be operated in square-wave modulation with a fundamental frequency from 100 Hz up to 1 kHz. For that the DC bus voltage of a back-to-back DC-link will be varied for
10 controllability of the arc current.

Generally, the features using power electronics in the line with the EAF is that the currents in the phases can be controlled which leads to a better performance of the EAF. Currents of variable frequency may be generated whereas a higher frequency (up to 1 kHz) results in a more stable arc.

- 15 Another feature that can be achieved is that the frequency of the current per phase can be different. Also, using power electronics the number of phases are not restricted to three, i.e. more electrodes in the EAF can be applied.

Using the power electronic converter the arc voltage can be easily controlled avoiding the use of a tap-changer.

- 20 A high frequency may be used during an EAF scrap melting period to stabilize arc and the frequency may be reduced during an EAF refining period.

- In EAF operation, arc instability mainly happens during scarp melting periods and it is mainly due to two reasons: un-uniform scrap composition,
25 and arc cooling down at the current zero crossings in AC power supply. EAF operated with 50/60 Hz is today limited with power input efficiency due to that the current is alternating with low frequency, and the arc has a tendency to cool off each time the current drops to zero. Re-establishment of a current flow in the reverse direction will take several hundred volts. High frequency
30 operation up to 1 kHz causes the current to change direction more often and

results in a stable arc. The arc stability is an important factor for power input efficiency which has been observed from DC EAF, arc welding and plant test of current swings. Variable and high frequency for EAF will improve power stability significantly and has a potential to increase steel productivity.

- 5 A method for operating an EAF is presented. The method comprises converting, in a power electronic converter, a grid frequency to an operating frequency for an EAF, controlling, in the power electronic converter, the converted operating frequency between over the grid frequency and 1 kHz, and operating one of more electrical arc(s) of the EAF with the controlled
10 converted operating frequency.

The EAF may comprise more than one electric arc, and the power of each electric arc is controlled individually by controlling the converted operating frequency between over the grid frequency and 1 kHz.

- The EAF may be operated with a power of at preferably least 50 MW, 100
15 MW, optionally for melting metal scrap.

The power electronic converter may comprise a rectifier connected to one or more inverters.

The AC EAF may comprise three or more than three electric electrodes. Cave-in during scrap melting is reduced with increasing number of electric arcs.

- 20 The EAF may comprise at least four electric arcs, and the electric arcs may be controlled separately in groups.

The converted operating frequency may during melting be controlled between 100 Hz and 1 kHz for sinusoidal, trapezoidal or square wave.

- A method for operating an EAF is presented. The method comprises
25 converting, in a power electronic converter (voltage and or current source type), a grid frequency to an operating frequency for an EAF, controlling, in the power electronic converter, the converted operating frequency between

100 Hz and 1 kHz, and operating one or more electrical arc(s) of the EAF with the controlled converted operating frequency.

The EAF may comprise more than one electrode, wherein the power of each electric arc is controlled individually. The individual control may comprise
5 individually controlling voltage, current and frequency. The power of each electric arc may be controlled individually by individually controlling voltage and current magnitudes and phase angles.

The EAF may be operated with a power of at least 50 MW, preferably about 100 MW, optionally for melting metal scrap.

10 The power electronic converter may comprise a rectifier connected to one or more inverters.

The EAF may comprise three or more electric electrodes.

The EAF may comprise at least four electric electrodes and the electric arcs are controlled separately in groups.

15 The converted operating frequency may during melting be controlled between 100 Hz and 1 kHz.

A power electronic converter for operating an EAF is presented. The power electronic converter comprises an inverter configured to convert a grid frequency to an operating frequency for an EAF, to control the converted
20 operating frequency between 100 Hz and 1 kHz, and to operate one or more electrical arc(s) of the EAF with the controlled converted operating frequency.

The converted operating frequency may be controlled between 100 Hz and 1 kHz during melting in the EAF.

25 The inverter may be configured to control the converted operating frequency between 100 Hz and 1 kHz individually for more than one electric arc of the EAF.

The power electronic converter may be a matrix converter.

The power electronic converter may comprise a thyristor rectifier, wherein the inverter is an MMC.

5 The power electronic converter may comprise a diode rectifier, wherein the inverter is an MMC.

The power electronic converter may comprise an MMC operated as a rectifier, wherein the inverter is a 2L or a 3L inverter.

10 The power electronic converter may comprise a rectifier providing power to at least two inverters arranged in parallel. The at least two inverters may be connected to a common three-phase EAF transformer. The at least two inverters may in an alternative be connected to separate three-phase EAF transformers, which in turn are connected in parallel to supply three EAF electrodes.

15 The power electronic converter may comprise a rectifier providing power to at least three inverters arranged in parallel. The at least three inverters may be connected to separated one-phase EAF transformers, which in turn are separately connected to three EAF electrodes. The power electronic converter may comprise at least six inverters that are connected to separate one-phase EAF transformers, which in turn are paired together in parallel and supply
20 three EAF electrodes.

The one-phase EAF transformers may be connected to the EAF electrodes in series instead of in parallel.

25 The power electronic converter may comprise a rectifier providing power to six inverters arranged in parallel, wherein each primary winding of a three-phase EAF transformer is connected to two of the inverters. The power electronic converter may comprise a DC-link between the rectifier and the six inverters, which DC-link has three bus-bars.

The power electronic converter may comprise a rectifier providing power to at least two inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, each in turn connected to at least two EAF electrodes.

- 5 The power electronic converter may comprise a rectifier providing power to at least four inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, which are grouped in pairs, and which pairs each in turn are connected to at least two EAF electrodes.

- 10 The power electronic converter may comprise a rectifier providing power to at least six inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, which are grouped in threes, and which group each in turn are connected to at least three EAF electrodes.

- 15 The power electronic converter may comprise a rectifier, and at least two inverters connected in series to the rectifier and connected in parallel to an EAF transformer. The inverters may be isolated galvanically between input and output.

The power electronic converter may comprise a rectifier, and at least three inverters connected in series to the rectifier and connected in parallel to multiple primary windings on an EAF transformer.

- 20 The power electronic converter may comprise a current source rectifier, wherein the inverter is a current source inverter.

When the power electronic converter comprises a rectifier, the rectifier may be a single unit or several units in parallel or in series.

- 25 An EAF system is presented. The EAF system comprises a power electronic converter, one or more EAF transformer(s), and an EAF.

A power transformer for supplying an EAF with power is presented. The power transformer supplies power to the EAF at frequencies between 100 Hz

and 1 kHz, and is configured to supply power to one of more electrical arc(s) of the EAF with the operating frequencies.

The power transformer may comprise:

5 a magnetic circuit of amorphous or nano-crystalline materials, with Iron Nitride based material, nano-crystalline material, to support variable frequency operation, or GO material with dimension designed to avoid saturation at higher frequency, wherein the core may be toroidal, stacked or wound;

10 windings with continuously transposed thin copper strands or Litz- wire, the mechanical strength of the conductor may be enhanced by epoxy glue or may be reinforcement by steel reinforced or by strong fibre composites, such as carbon fibre, or the winding conductor may be shielded magnetically to keep the winding strand thick while reducing the eddy loss, wherein the primary and secondary windings may be parallel, however with different number of
15 turns, without distance between them to remove leakage inductance in the transformer, and to reduce short circuit inductance inter wound windings may be used, or long and thin transformer structures may be used;

insulation system may comprise conventional oil and paper insulation or natural/synthetic esters impregnated high temperature insulation or any
20 other suitable insulation with enhanced partial discharge resistant properties using nano fillers; and

thermal management and hot spot mitigation may be provided by active management of hot spot by heat pipe, wherein the conductor may have an in-built cooling channel.

25

The invention has mainly been described above with reference to a few embodiments. However, as is readily appreciated by a person skilled in the art, other embodiments than the ones disclosed above are equally possible within the scope of the invention, as defined by the appended patent claims.

CLAIMS

1. A method for operating an electric-arc furnace, EAF, comprising:
 - converting, in a power electronic converter, a grid frequency to an operating frequency for an EAF;
 - 5 - controlling, in the power electronic converter, the converted operating frequency between 100 Hz and 1 kHz; and
 - operating one or more electrical arc(s) of the EAF with the controlled converted operating frequency.
2. The method according to claim 1, wherein the EAF comprises more than
10 one electrode, and the power of each electric arc is controlled individually.
3. The method according to claim 2, where the power of each electric arc is controlled individually by individually controlling voltage and current magnitudes and phase angles.
4. The method according to claim 1 or 2, wherein the EAF is operated with
15 a power of at least 50 MW, preferably about 100 MW, optionally for melting metal scrap.
5. The method according to any one of claims 1 to 4, wherein the power electronic converter comprises a rectifier connected to one or more inverters.
6. The method according to any one of claims 1 to 4, wherein the EAF
20 comprises three or more electric electrodes.
7. The method according to any one of claims 1 to 6, wherein the EAF comprises at least four electric electrodes and the electric arcs are controlled separately in groups.
8. The method according to any one of claims 1 to 7, wherein the converted
25 operating frequency is during melting controlled between 100 Hz and 1 kHz.

9. A power electronic converter for operating an electric-arc furnace, EAF, the power electronic converter comprising an inverter configured to convert a grid frequency to an operating frequency for an EAF, to control the converted operating frequency between 100 Hz and 1 kHz, and configured to operate one of more electrical arc(s) of the EAF with the controlled converted operating frequency.
10. The power electronic converter according to claim 9, wherein the converted operating frequency is controlled between 100 Hz and 1 kHz for melting.
- 10 11. The power electronic converter according to claim 9 or 10, wherein the inverter is configured to control the converted operating frequency between 100 Hz and 1 kHz individually for more than one electric arc of the EAF.
12. The power electronic converter according to any one of claims 9 to 11, wherein the power electronic converter is a matrix converter.
- 15 13. The power electronic converter according to any one of claims 9 to 11, comprising a thyristor rectifier, and wherein the inverter is a Modular Multi-Level Converter, MMC.
14. The power electronic converter according to any one of claims 9 to 11, comprising a diode rectifier, and wherein the inverter is a Modular Multi-Level Converter, MMC.
- 20 15. The power electronic converter according to any one of claims 9 to 11, comprising a Modular Multi-Level Converter, MMC, operated as a rectifier, and wherein the inverter is a 2L or a 3L inverter.
16. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier providing power to at least two inverters arranged in parallel.
- 25 17. The power electronic converter according to claim 16, wherein the at least two inverters are connected to a common three-phase EAF transformer.

18. The power electronic converter according to claim 16, wherein the at least two inverters are connected to separate three-phase EAF transformers, which in turn are connected in parallel to supply three EAF electrodes.
19. The power electronic converter according to any one of claims 9 to 15,
5 comprising a rectifier providing power to at least three inverters arranged in parallel.
20. The power electronic converter according to claim 19, wherein the at least three inverters are connected to separated one-phase EAF transformers, which in turn are separately connected to three EAF electrodes.
- 10 21. The power electronic converter according to claim 19, comprising at least six inverters that are connected to separate one-phase EAF transformers, which in turn are paired together in parallel and supply three EAF electrodes.
- 15 22. The power electronic converter according to any one of claims 16 to 21, wherein the one-phase EAF transformers are connected to the EAF electrodes in series instead of in parallel.
23. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier providing power to six inverters arranged in parallel, wherein each primary winding of a three-phase EAF transformer is
20 connected to two of the inverters.
24. The power electronic converter according to claim 23, comprising a DC-link between the rectifier and the six inverters, which DC-link has three bus-bars.
- 25 25. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier providing power to at least two inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, each in turn connected to at least two EAF electrodes.

26. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier providing power to at least four inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, which are grouped in pairs, and which pairs each in turn are connected to at least two
5 EAF electrodes.
27. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier providing power to at least six inverters arranged in parallel, each in turn connected to a one-phase EAF transformer, which are grouped in threes, and which group each in turn are connected to at least
10 three EAF electrodes.
28. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier, and at least two inverters connected in series to the rectifier and in parallel to an EAF transformer.
29. The power electronic converter according to claim 28, wherein the
15 inverters are isolated galvanically between input and output.
30. The power electronic converter according to any one of claims 9 to 15, comprising a rectifier, and at least three inverters connected in series to the rectifier and in parallel to multiple primary windings on an EAF transformer.
31. The power electronic converter according to any one of claims 9 to 15,
20 comprising a current source rectifier, and wherein the inverter is a current source inverter.
32. The power electronic converter according to any of claims 9 to 31, when comprising a rectifier, the rectifier being a single unit or several units in parallel or in series.
- 25 33. An electric-arc furnace, EAF, system, comprising a power electronic converter according to any one of claims 1 to 32, one or more EAF transformer(s), and an EAF.

36. A power transformer for supplying a electric-arc furnace, EAF with power at frequencies between 100 Hz and 1 kHz, and configured to supply power to one of more electrical arc(s) of the EAF with the operating frequencies.

5 37. The power transformer according to claim 36, comprising:

a magnetic circuit of amorphous or nano-crystalline materials, with Iron Nitride based material, nano-crystalline material, to support variable frequency operation, or GO material with dimension designed to avoid saturation at higher frequency, wherein the core may be toroidal, stacked or
10 wound;

windings with continuously transposed thin copper strands or Litz- wire, the mechanical strength of the conductor may be enhanced by epoxy glue or may be reinforcement by steel reinforced or by strong fibre composites, such as carbon fibre, or the winding conductor may be shielded magnetically to keep
15 the winding strand thick while reducing the eddy loss, wherein the primary and secondary windings may be parallel, however with different number of turns, without distance between them to remove leakage inductance in the transformer, and to reduce short circuit inductance inter wound windings may be used, or long and thin transformer structures may be used;

20 insulation system may comprise conventional oil and paper insulation or natural/synthetic esters impregnated high temperature insulation or any other suitable insulation with enhanced partial discharge resistant properties using nano fillers; and

thermal management and hot spot mitigation may be provided by active
25 management of hot spot by heat pipe, wherein the conductor may have an in-built cooling channel.

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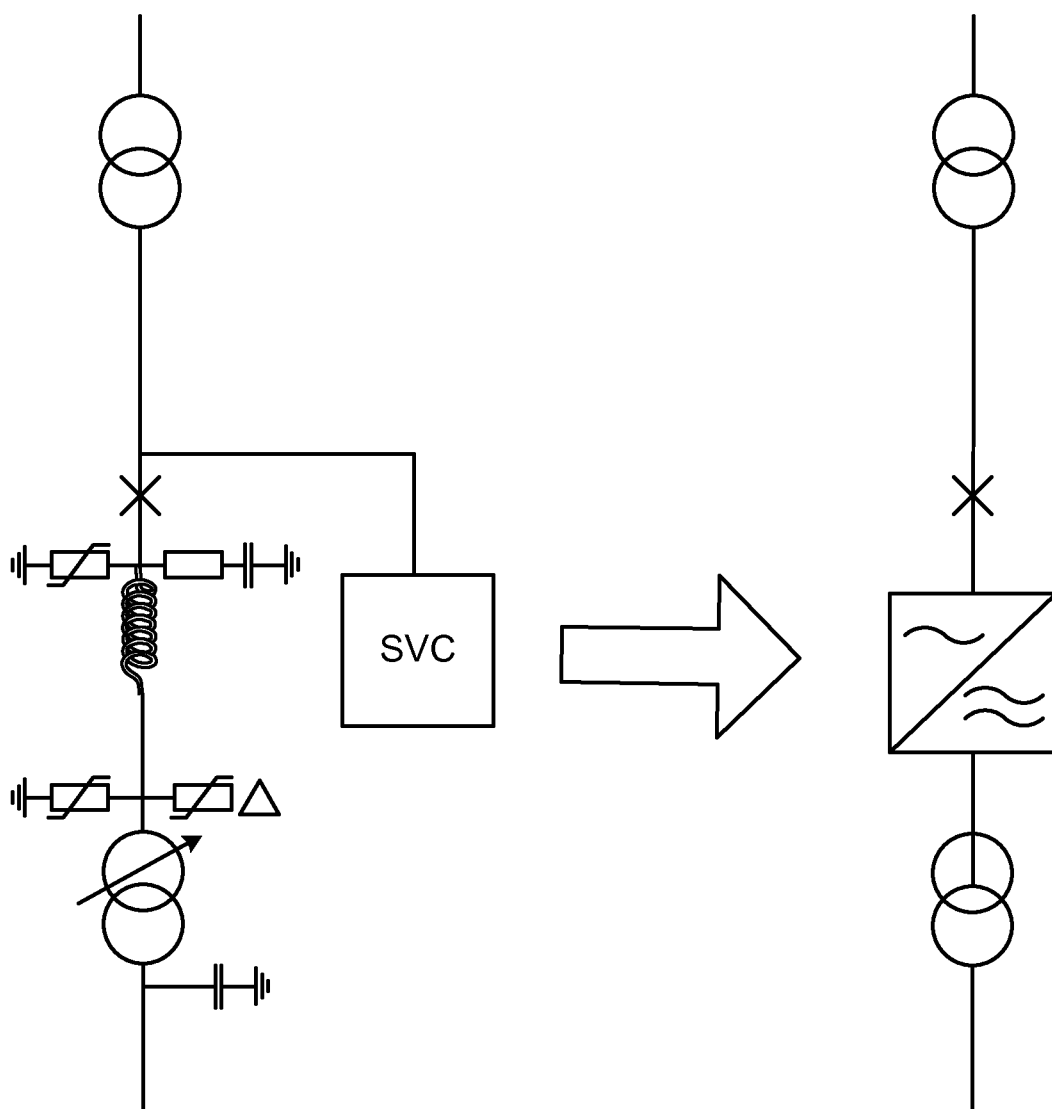
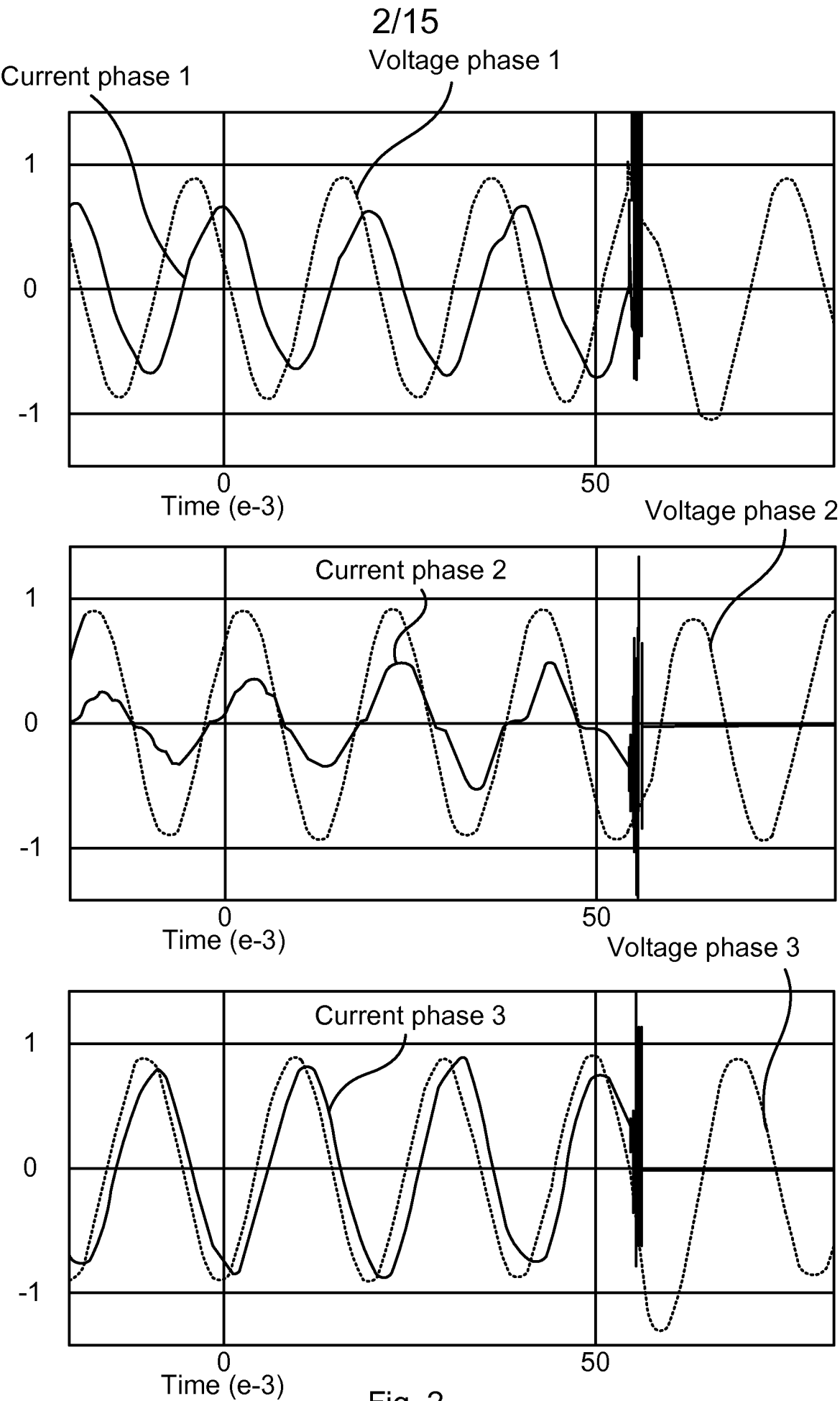


Fig. 1



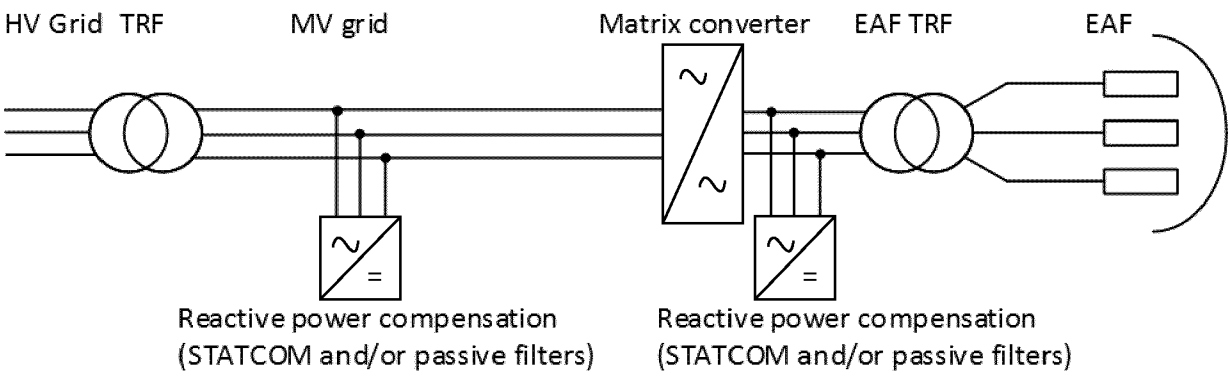


Fig. 3

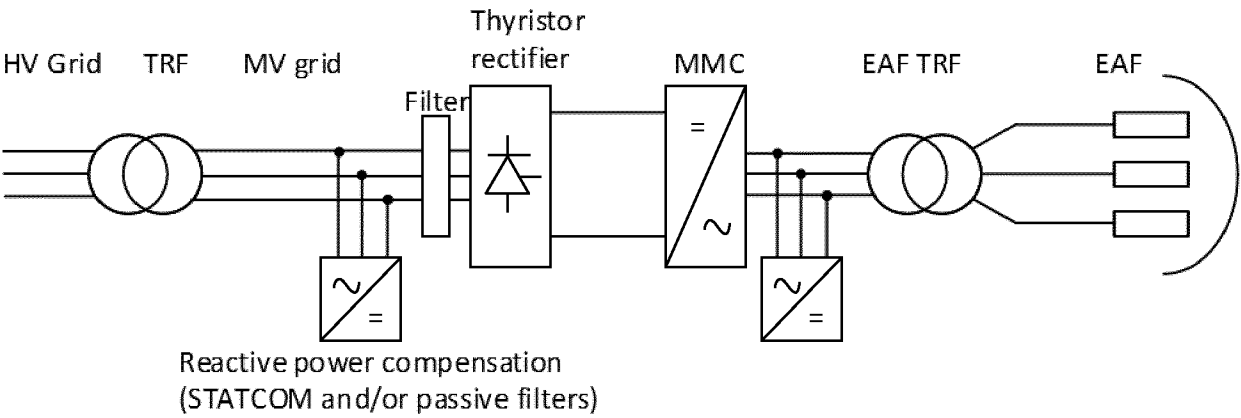


Fig. 4

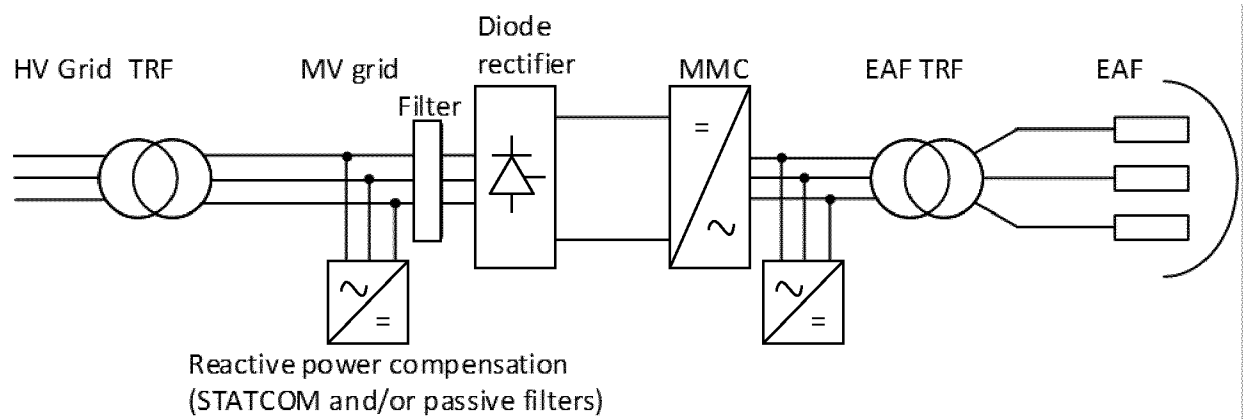


Fig. 5

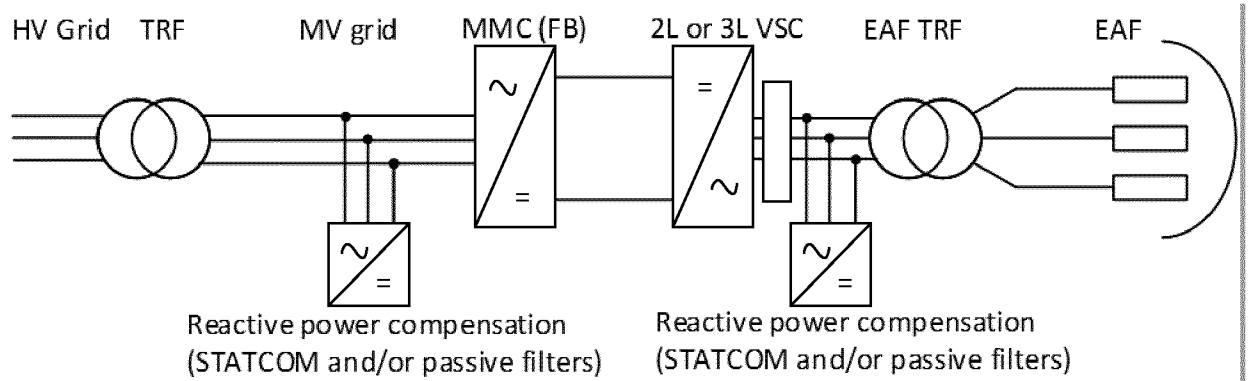


Fig. 6

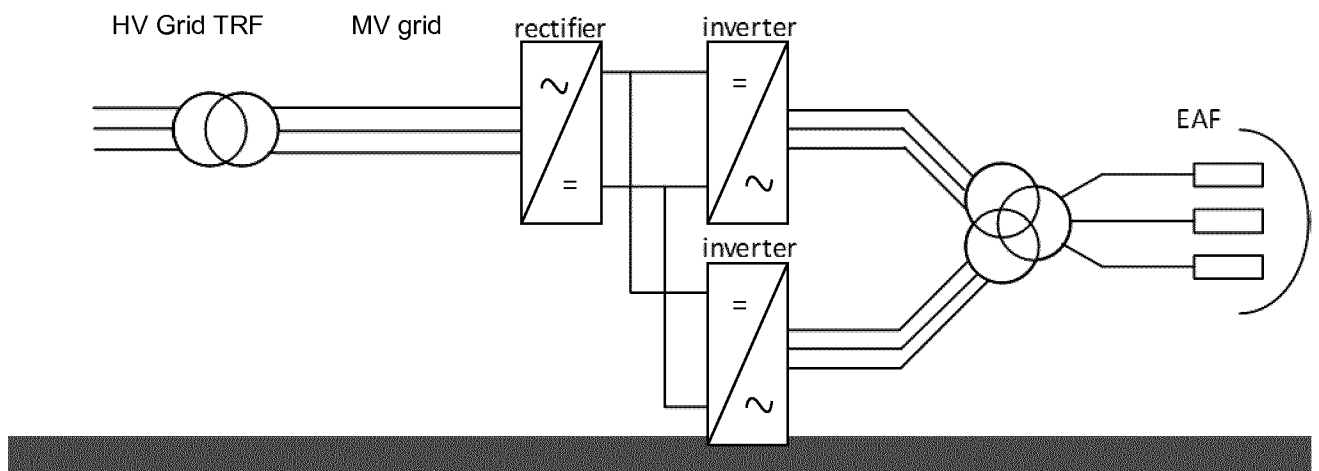


Fig. 7

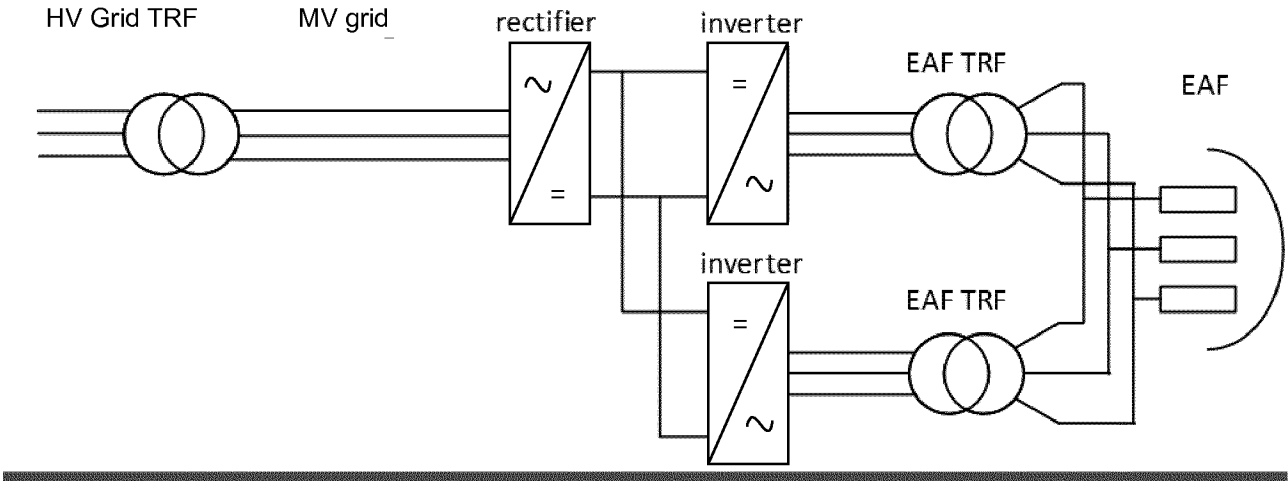


Fig. 8

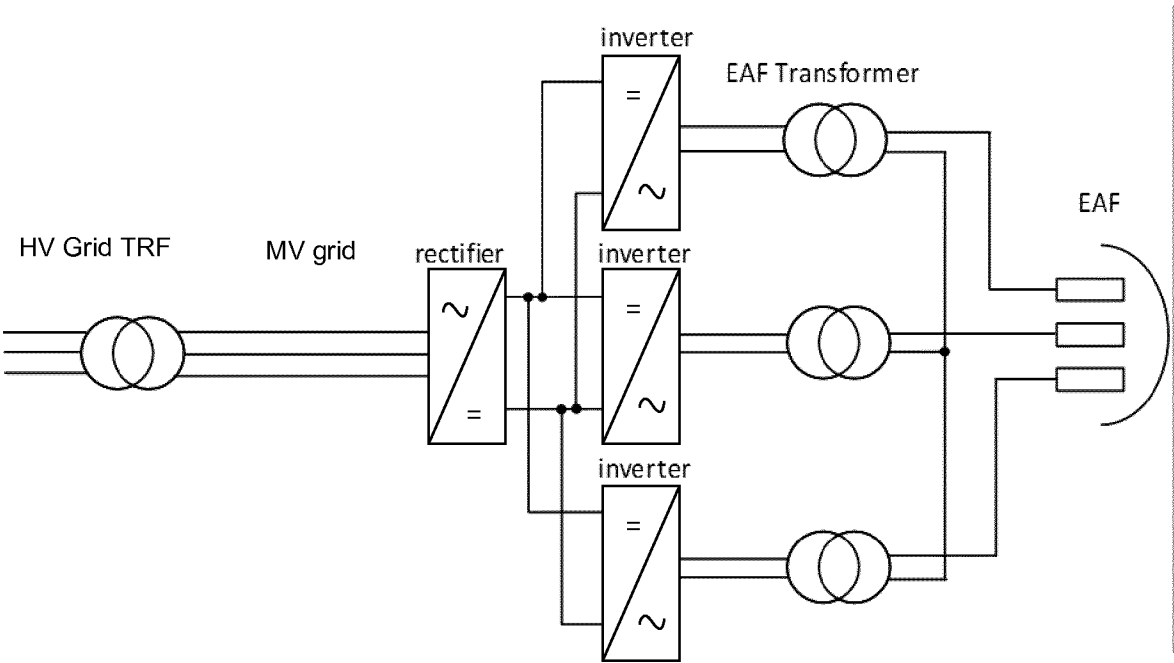


Fig. 9

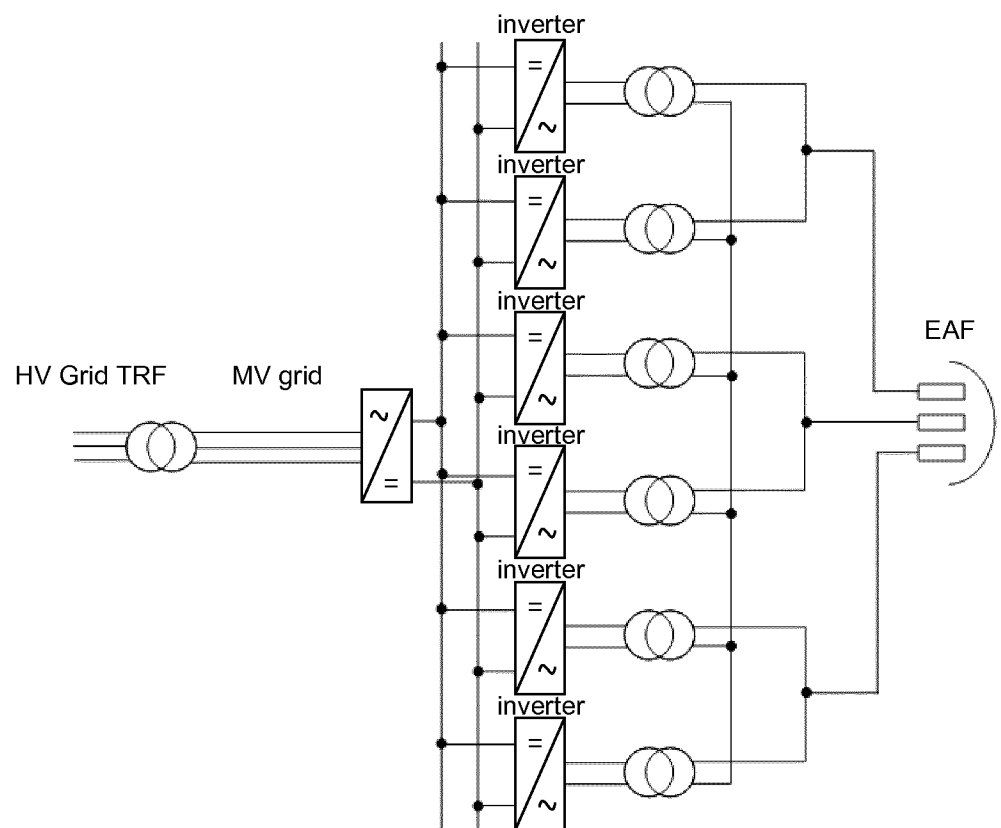


Fig. 10

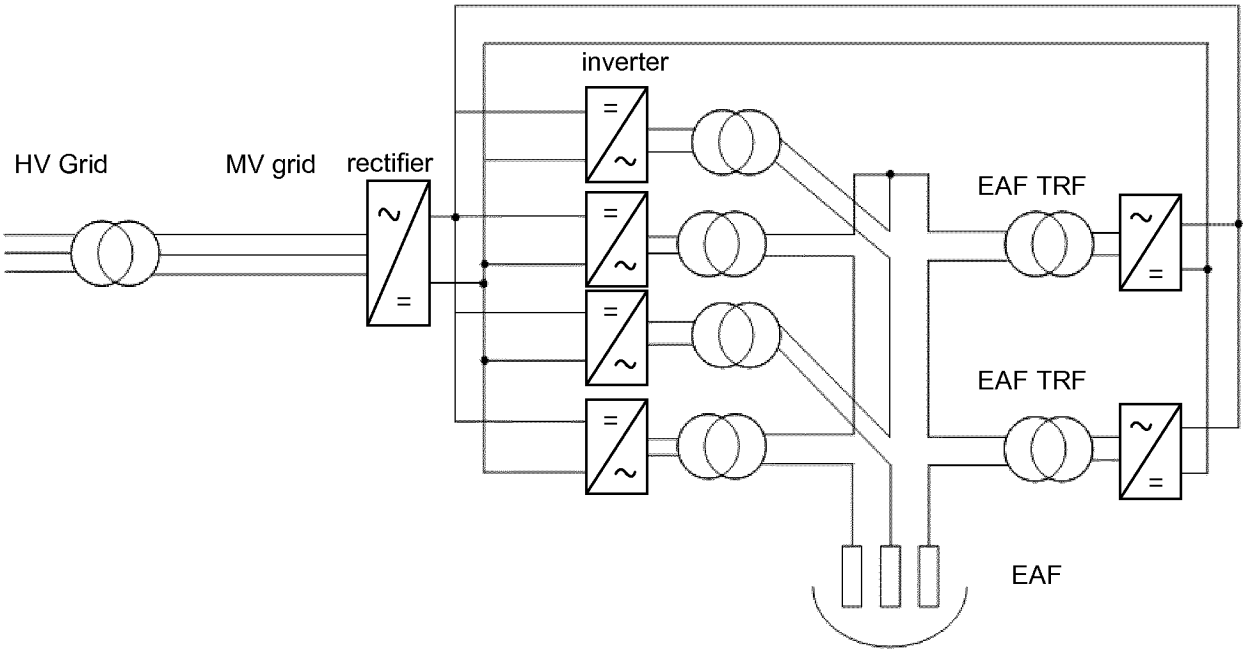


Fig. 11

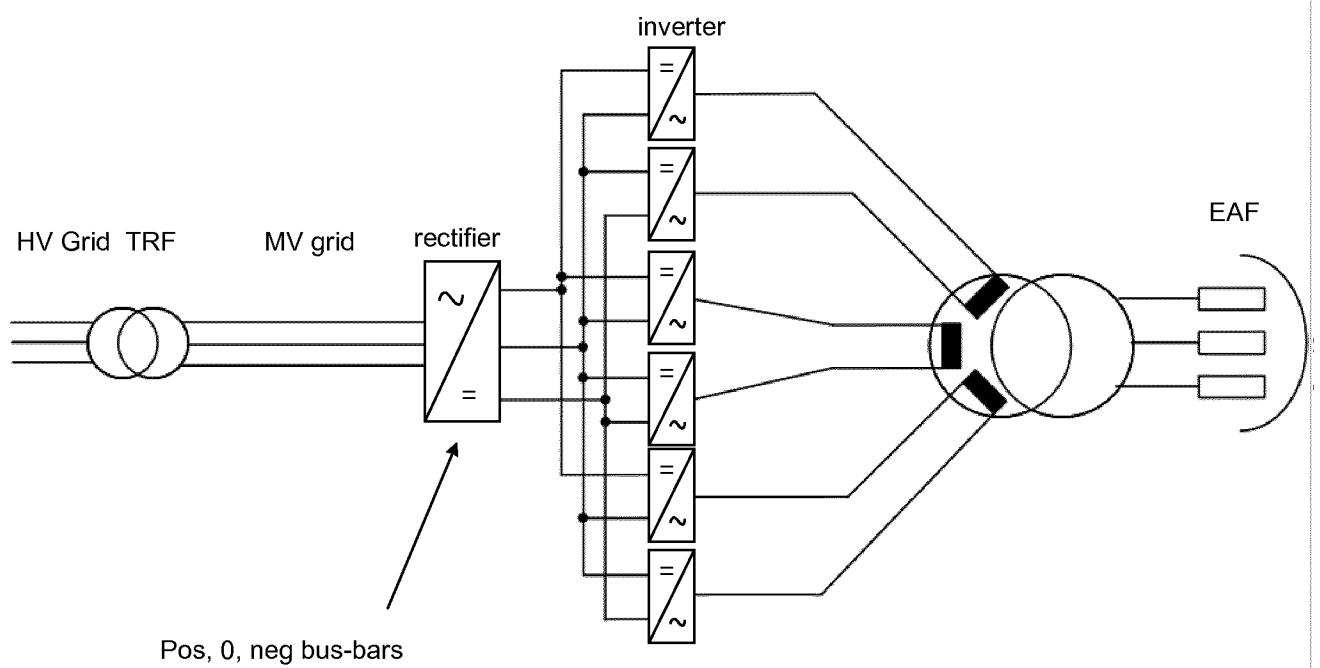


Fig. 12

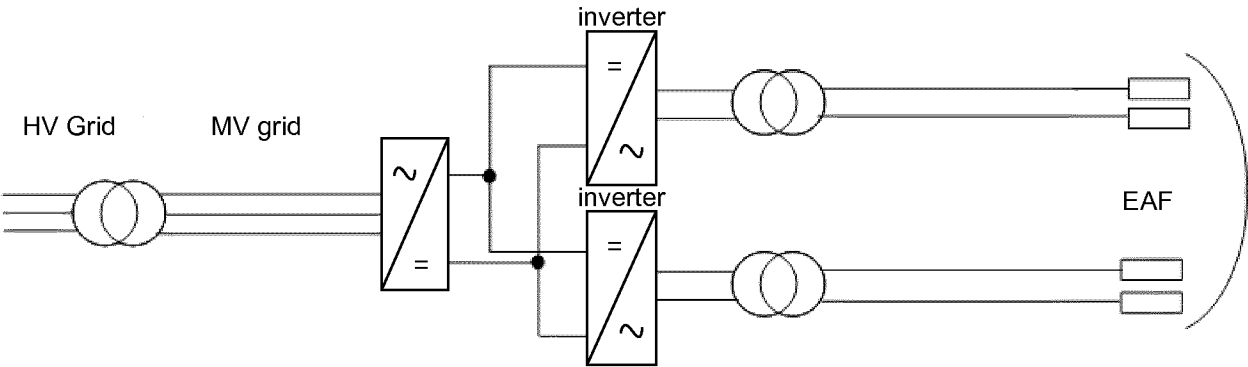


Fig. 13

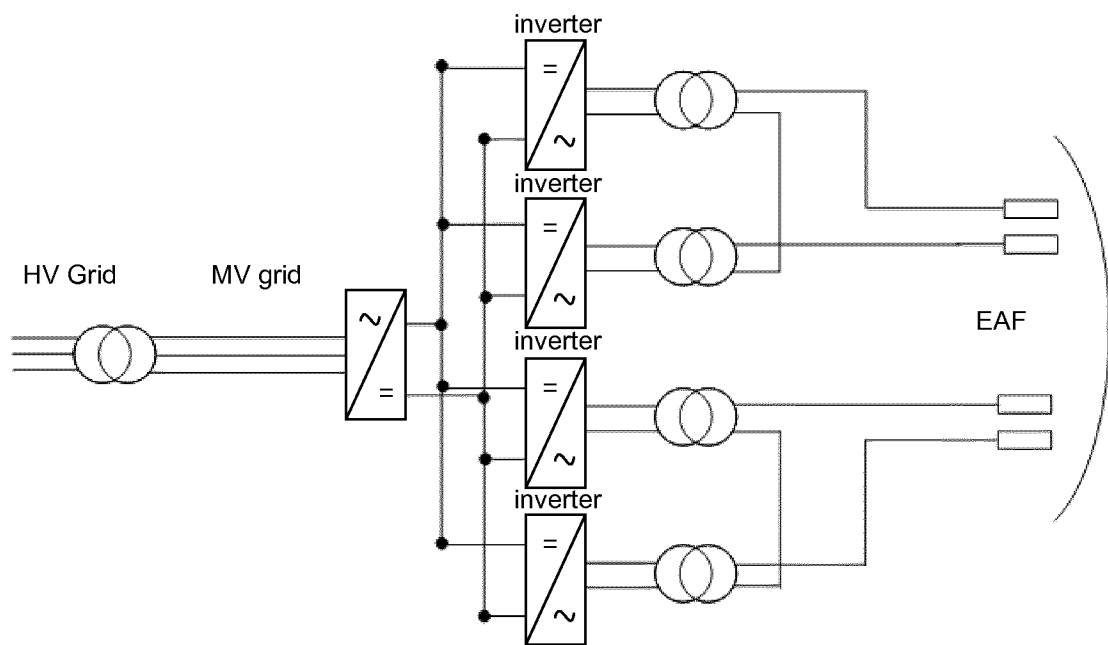


Fig. 14

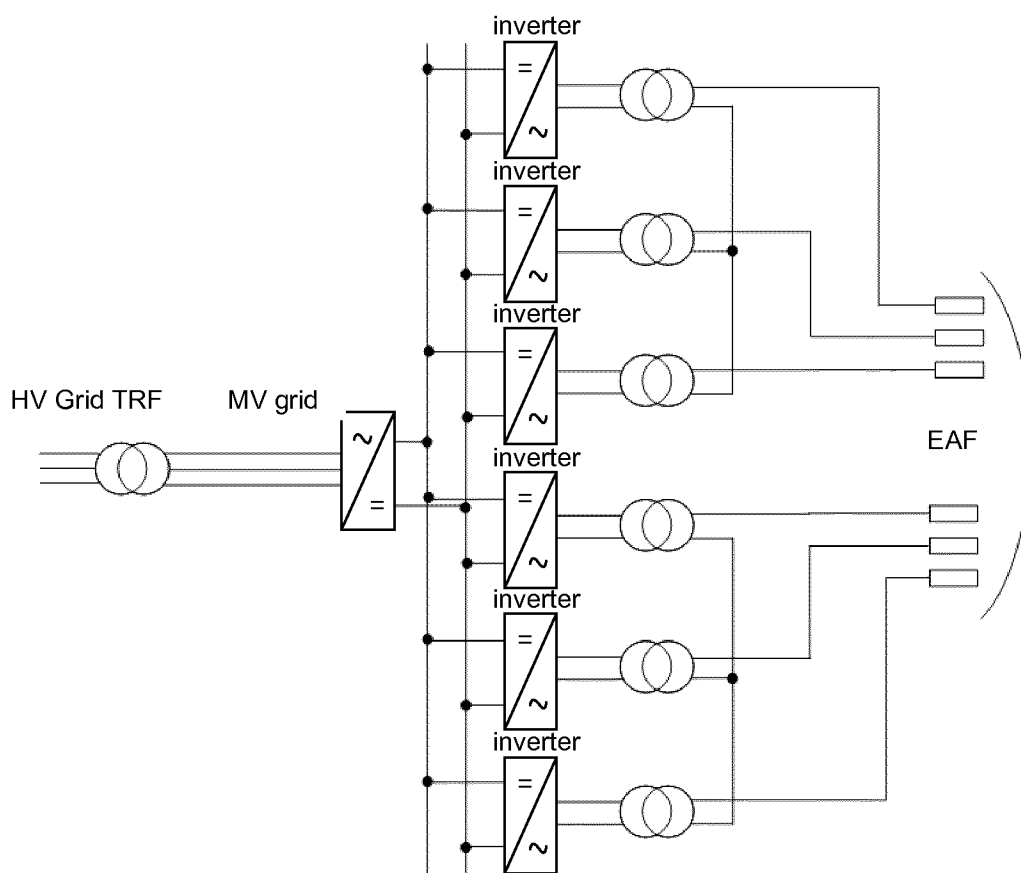


Fig. 15

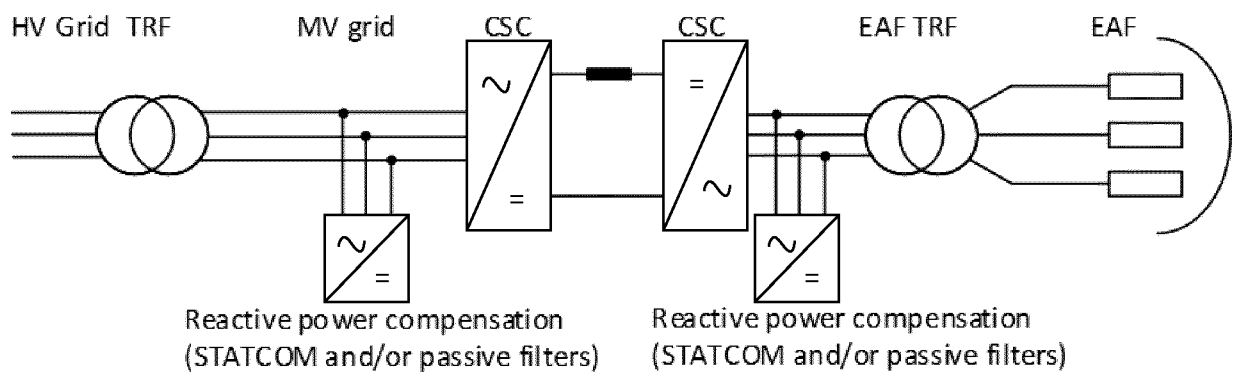


Fig. 16

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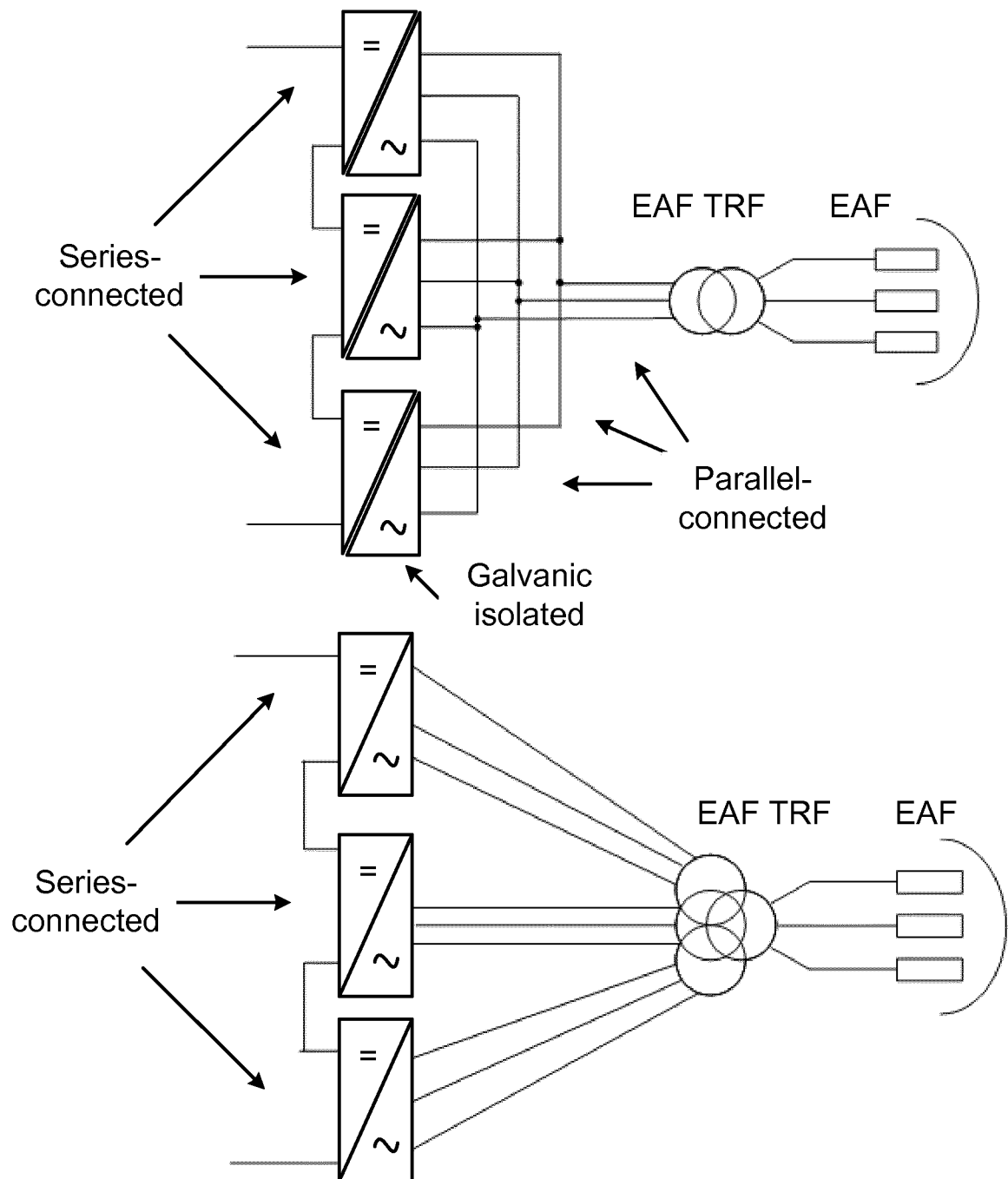


Fig. 17

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/065412

A. CLASSIFICATION OF SUBJECT MATTER
INV. H05B7/144
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H05B H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2016/023594 A1 (SIEMENS AG [DE]) 18 February 2016 (2016-02-18)	1-34
Y	abstract page 2, line 7 - line 22 page 3, line 34 - page 5, line 16 page 7, line 15 - page 12, line 19 page 13, line 26 - page 14, line 21 figures 1-12	35
X	WO 2010/097122 A1 (ABB TECHNOLOGY LTD [CH]; HASLER JEAN-PHILIPPE [SE]; HOSINI FALAH [SE];) 2 September 2010 (2010-09-02)	1-34
Y	abstract page 2, line 8 - page 5, line 19 page 6, line 2 - page 7, line 14 page 9, line 12 - page 10, line 6 page 13, line 9 - line 25 figures 1-7	35
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search

15 March 2018

Date of mailing of the international search report

26/03/2018

Name and mailing address of the ISA/

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Authorized officer

Chelbosu, Liviu

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2017/065412

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2017/027027 A1 (DOEBBELER ARNO [DE] ET AL) 26 January 2017 (2017-01-26)	1-34
Y	abstract paragraph [0004] - paragraph [0005] paragraph [0008] - paragraph [0037] paragraph [0043] - paragraph [0044] paragraph [0063] - paragraph [0067] paragraph [0070] - paragraph [0075] figures 1-4 -----	35
X	EP 3 121 949 A1 (TOKYO INST TECH [JP]) 25 January 2017 (2017-01-25)	1-34
Y	abstract paragraph [0002] paragraph [0005] paragraph [0007] paragraph [0033] paragraph [0042] - paragraph [0049] figures 1-9 -----	35
Y	US 2008/304300 A1 (RAJU RAVISEKHAR NADIMPALLI [US] ET AL) 11 December 2008 (2008-12-11)	35
A	abstract paragraph [0004] - paragraph [0008] paragraph [0038] - paragraph [0044] paragraph [0051] - paragraph [0054] figures 1-7 -----	1-34

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2017/065412

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