Prospects for IGBT application in electrical power converters for industrial high-current DC loads

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Abstract. The paper presents the research data of the electrical power converters used for a powering industrial vacuum DC arc furnace. The authors have analyzed energy performance of the power converter with a parametric current source (PCS) and the converter based on switched-mode power supply (SMPS) units with IGBT switches. The research shows that the converter with SMPS units has greater efficiency, thereby reducing specific energy consumption. To improve power quality in industrial power grids, which provide electricity to high-current DC loads, a converter design based on current-source-type active rectifiers is proposed. The simulations carried out by the authors have shown that desynchronization of AR switching processes in the proposed converter system allows one to reduce total harmonic distortion (THD) of the mains voltage.

1. Introduction

Electrical DC power is widely used in various industrial applications, and a significant part of it is consumed by ferrous and non-ferrous metallurgy. The most common DC loads in those industries are electrolysis plants for the production of non-ferrous and rare earth metals, electric arc furnaces for melting and processing metals and ores, regulated high-power electric drives for rolling mills. Due to high-energy intensity of those consumers their power ratings are measured up to hundreds of megawatts, operating currents – tens and hundreds of kiloamperes.

Taking into account all of the above, studies aimed at improving the efficiency of industrial power converters for high-current DC consumers are a relevant and promising direction of research [1-3].

2. Industrial DC sources

The specificity of consumers imposes a number of requirements on industrial DC sources. The voltage and current of the electrolyzers must be promptly adjusted in a wide range alongside the ability of maintaining them with the accuracy of 0.1–0.2 % of rated value [4, 5]. The required range of voltage regulation (20-100 %) and compensation of mains voltage deviations (up to ±10 %) are provided by applying transformer with the on-load tap changer (OLTC).

Accurate regulation inside the OLTC step range is performed by saturable reactors connected in series with diodes; phase-controlled thyristors are also commonly used for this purpose. Due to features of technological process, power converters operate with a non-zero firing angle for 90 % of the time. Therefore their power factor is 0.7–0.91 [5]. PCS are also applied to supply low- and medium-power industrial DC loads. However this type of converters does not allow accurate regulation of output.
current, and is designed to have rated leading power factor of 0.9 [6]. These circumstances cause increase in electricity consumption and forces to inflate power rating of electrical equipment.

In addition, semiconductor converters are a non-linear load, which significantly affects the power quality in the supply grid. The constantly changing parameters of load and network, in addition to the fact that main generated harmonics have low order, drastically reduce the efficiency and service life of filter-compensating devices. In these conditions, a common alternative solution to power quality management is to use power transformers with split secondary windings. One winding is Y-connected and the other one is Δ-connected which doubles harmonics order.

3. Fully-controlled power semiconductor switches connected in parallel
Power supply for application with relatively small DC load currents is usually carried out on SMPS with power factor correction, which uses gate-turn-off (GTO) thyristors, metal-oxide-semiconductor-field-effect-transistors (MOSFET) and insulated-gate-bipolar-transistors (IGBT). IGBTs demonstrate superior efficiency in switch-operated mode if high-power rating and commutated currents are required, which has led to their widespread use in area of high-power converters.

High-power IGBT are issued in modules. High-current modules contain three paralleled transistors with total commutated current up to 3.6 kA (7.2 kA in critical conductivity mode) with operating voltages 1700 V [7]. Further increase in current is achieved by connecting modules in parallel to form a single semiconductor pack. With an increasing number of modules in a pack, the scatter of control circuits parameters is also rising, which leads to non-simultaneous commutation transients inside a pack and transistors with lowest switching time will be overloaded. Current distribution is also influenced by the deviation between rated and actual forward voltage drop of IGBT power circuit in saturation mode. Due to these factors, the number of IGBTs in a single pack is limited and the overall current has to be derated [8].

Current imbalance coefficient \( k_b \) for a single semiconductor pack is defined as:

\[
k_{ib} = \frac{I_{c_{max}}}{I_{avg}} - 1 ,
\]

where \( I_{c_{max}} \) is collector current of the most loaded IGBT, which should not exceed the maximum value, defined by the manufacturer; \( I_{avg} \) is average current of a single transistor in the semiconductor pack.

Generally \( k_{ib} \) is in the range of 5–20 %, and lower values of \( k_{ib} \) correspond to IGBT with the highest power rating. Additionally, most of the IGBTs have a negative temperature coefficient, which helps to ensure current balancing within single pack.

Considering \( k_{ib} \) we get load factor for semiconductor pack as follows:

\[
k_{lf} = \left( T -Tk_{ib} + 2k_{ib} \right) \left( T +Tk_{ib} \right) ^{-1} ,
\]

where \( T \) is number of transistors in pack.

From all of the aforesaid, utilizing IGBT in power converters is a promising way to improve the energy efficiency of industrial power supplies for high-current DC consumers.

4. The object of research and parameters of power supply grid
The object of research is located at a foundry enterprise, which operates vacuum DC electric arc furnaces (type 833D). Furnaces of this type use consumable electrodes and are intended for casting stainless, structural, refractory and heat-resistant alloys based on titanium. No-load voltage for the furnace is 60 V, and arc operating voltage is 30-40 V, maximum arc current is 16 kA. This corresponds to power consumption of 500-600 kW.

Electrical power consumption and power quality data for 220/380 V 50 Hz mains supply grid were obtained using certified measuring equipment, which includes “Resource UF2M” and “Fluke 42B”. During the 24-hour period, mains voltage deviations did not exceed 2 % even with operational arc furnaces. With inoperative furnaces, voltage THD at supply grid connection point was under 3%.

4.1 Power converter with PCS
PCS implements the output characteristic of current source, thus no-load mode operation must be prevented. With this in mind, the power source design consists of two parallel power converter units. The power circuit schematic of the converter with PCS is shown in figure 1. The broken lines show the magnetic cores for step-down transformers T1 and T2.

![Power Circuit Schematic](image)

**Figure 1.** The power circuit schematic of the converter with PCS.

When the switch S1 is closed, the starting converter unit with no-load voltage of approximately 50 V is turned on. It is used to create an electric arc while the resistance of the interelectrode space is still large. This power source consists of a transformer T1 and three-phase full bridge diode rectifier on semiconductor sets V1–V6. Each set contains 11 separate diodes connected in parallel and RC-snubber circuits.

Once the stable electric arc is occurred, the main converter unit is put into operation using the switch S2. Due to resonance in the reactive elements L1–L3 and C1–C3, PCS ensures constant load current when its resistance fluctuates in a wide range. The regulation of the load current in increments of several kiloamperes is carried out by switching the primary coupling taps of transformer T2. Operating arc voltage is maintained manually by interelectrode space variation. The rectifier uses diode sets V7–V12 (similar to V1–V6, but with a larger number of diodes) which are connected in three-phase double-wye with an interphase transformer (L4) configuration. The diagrams of active and reactive power consumption, corresponding to melting operation with arc current value of 9.7 kA, are presented in figure 2.

![Power Consumption Diagrams](image)

**Figure 2.** The diagrams of active and reactive power consumption for the PCS converter.
During melting, the leading power factor of the PCS converter was within 0.86–0.95. An average input current value was 780 A per phase that, with arc current and interelectrode voltage of 33 V, corresponds to the converter efficiency of 0.69. Mains supply grid voltage THD was below 5.7 %, the converter total input current THD was 26–30 % for steady state operation.

4.2. Power converter with SMPS units
This type of DC power supply contains 90 SMPS units connected in parallel, its output characteristic is also close to a current source. However, this design utilizes pulse-width modulation (PWM) control, which allows smooth and accurate control of output current, thus making it operational in no-load mode. Arc operating voltage is regulated similarly to PCS converter. Single SMPS unit parameters are listed below in table 1.

| Parameter                                      | Value          |
|-----------------------------------------------|----------------|
| Input linear voltage range                    | 380 V ±15 %    |
| Power rating with maximum output current      | 8.6 kVA        |
| Output no-load voltage                        | 45 V           |
| Maximum output current with environment       | 180 A          |
| Current regulation range                      | (5÷180) A      |
| Maximum output power                          | 8.1 kW         |

Power circuit schematics of the single SMPS unit and the converter overall energy consumption diagrams are listed in figure 3. Unlike PCS power supply, the converter with SMPS units uses up to 15-16 kVA in standby mode for maintaining operations of control and cooling systems.

The three-phase full bridge rectifier of input cascade implements diodes VD1-VD6. This causes the same input current harmonics as a power converter with PCS. However, these diodes operate on voltage of the mains power grid, which reduces the value of commutated currents and switching losses. Each of the switches VT7-VT10 contains two IGBTs connected in parallel, forms a power inverter which supply power to high-frequency ferrite transformer T. The output two-diode bridge single-phase rectifier

![Figure 3. SPMS unit power circuit schematic (a) and diagrams of active and reactive power consumption for SPMS power supply (b).](image)
contains diode sets VD11-VD12 and uses reactor L to reduce current ripple. High carrier frequency of PWM (150 kHz) allows one to reduce the dimensions of the transformer and output filter.

During melting operation, the lagging power factor was close to 0.97–0.98. An average input current value was 780 A per phase, arc operating current and voltage value were 12 kA and 33 V, respectively. This gives the power converter efficiency of 0.8. For steady state operation voltage THD was under 6.9 %, input current THD was 30–32 %. As a result, rise of 20 % for arc current leads to increased furnace operating temperature, therefore improving casting quality and reducing overall process time.

Accordingly to the research of experimental data was revealed that the power converter based on SMPS units has better energy performance and current regulation accuracy than converter with PCS. However, none of considered in this paper DC power supply designs allows one to improve electromagnetic compatibility (EMC) with the power supply network.

5. Improving EMC with mains power supply grid
The article [9] proposed powering an industrial aluminum electrolyzer manufactory with a partitioned DC power supply converter system based on high-power current-source-type AR. Besides power factor correction combined with ability of smooth and accurate current regulation within range from zero to rated value, AR allows one to form sinusoidal input currents. However, if rectifiers are connected in parallel and their switching processes are simultaneous, input harmonics level is increased in proportion to the number of converters. [10]. To avoid this, PWM carrier signals of ARs inside each section should be phase-shifted relatively to each other. This leads to different switching times of separate ARs and increases the order of generated harmonics, which result in decreasing of voltage and current THD [11]. Therefore to evaluate the effectiveness of this method, the simulation in Matlab Simulink was carried out. The simulation included the power converter with six current-type-source ARs connected in parallel. PWM carrier signal frequency is 2 kHz. Oscillogram of power supply grid phase voltage with single operating AR with power rating of 0.5 MVA is shown in figure 4a, voltage THD was 2.35 %. Figure 4b presents the same voltage diagram but in this case six AR are operational with synchronized switching times, which leads to the voltage THD value of 14.12 %.

![Figure 4. Mains power grid phase voltage oscillogram for converter with one operational AR (a), six operational ARs with synchronized switching times (b), six operational ARs with desynchronized switching times (c).](image)

In figure 4c switching times of all six ARs are desynchronized, phase shifts between PWM carrier signals are the same value. Starting phase $\psi_i$ for each carrier signal is defined by:

$$\psi_i = 2\pi (i - 1) A^{-1}$$

where $i$ is AR index number and $A$ is amount of paralleled ARs. THD in this case was 7.75 %, which is significantly less than THD for synchronized switching times. It should be noted that deviation from calculated phase shift angle values (3) leads to an increase in harmonics.
Growth in the number of ARs results in decreasing phase shift angles, their minimal value is limited by speed of the control system and accuracy of voltage and current measuring sensors. Additional research is required to evaluate the impact of these factors on EMC.

6. Conclusion
Analysis of theoretical and experimental data has shown that using of SMPS units or ARs based on parallel IGBT modules for application in industrial power supply for powering high-current DC loads improves the converter energy performance. Proposed converter designs allow smooth and accurate current regulation within a wide range without a decrease in the overall power factor. This makes it possible not only to decrease power rating of electrical equipment used, but also discard OLTC in power transformers and reduce specific consumption of electrical energy.

The method for reducing voltage and current THD by desynchronizing current-type-source ARs switching processes, described in the paper, makes possible to maintain EMC of the power converter system and power supply grid. This provides an increase in service life of electrical equipment and reduces the number of faults and false positives of protective automation devices.

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