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Comparison of Electrostatic Precipitator Power Supplies with Low Effects on the Mains

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***Abstract*-- In this article, the distortions caused by the power supplies employed in Electrostatic Precipitators (ESP) are investigated, and means for improving the line power quality are proposed. Multi-pulse and PWM rectifier topologies and other concepts including hybrid systems and active filters are evaluated in order to identify suitable systems for ESP applications. A comparison of the studied systems rated to 60 kW and fully designed employing commercial components is shown. The ESP systems efficiency, power density, current harmonic THD, among others features are used for the assessment. The loss calculations are extended to a variable chip area to allow a fair comparison between the studied systems. Finally, the VIENNA 6-switches rectifier and active filter concepts are chosen and experimental analyses are carried out, verifying the performance and feasibility of the proposed systems.**

***Index Terms*—Electrostatic precipitators, rectifier systems, LCC resonant converter.**

I. Introduction

Electrostatic Precipitators (ESPs) are dust collectors, consisting of parallel electrodes that use electrostatic charges to separate pollutant particles in the entering gas. High power converters are commonly used to supply energy to the plates of the ESP at a high voltage level. These power supplies have a typical output power range of 10 kW to 120 kW and output voltage range of 30 kVdc to 100 kVdc [1]-[8].

Modern power supplies for ESPs are based on resonant converters in order to utilize the parasitic elements of the high voltage transformer in the circuit operation and to obtain soft switching for a wide operating range. Fig. 1 shows a typical circuit diagram of an ESP power supply. This system commonly employs a 3-phase diode bridge rectifier as a front-end converter due to its simplicity, reliability, and low cost. The main drawback of this concept is that diode rectifiers inject significant current harmonics into the power grid. This could overload the nearby shunt capacitors, or distort the voltage at the point of common coupling. Therefore, simple rectifiers do not meet the IEEE 519 guidelines. Especially in pulsed operation, a drastically imbalanced loading of the mains phases could occur [2]. Accordingly, the concept employed today bears the risk of causing severe problems, such as malfunction of other equipment fed by the same grid, audible noise, increased losses of transformers, generators, and power lines.

In order to fulfil mains power quality requirements, i.e. IEEE 519, the overall influence of the modern ESP power supplies on the mains power quality is studied in this article and means for improving the line power quality are proposed. Section II aims to provide a better understanding of the interaction between the ESP power supply and the grid. In Section III, suitable systems for ESP applications are sought; Multi-pulse and PWM rectifier topologies and other concepts including hybrid systems and active filters are investigated as replacements for 3-phase diode bridge rectifiers. A comparison of the studied systems rated to 60 kW and fully designed employing commercial components is shown in Section IV. The ESP systems' efficiency, power density, current harmonic THD, among other features, are used for the assessment. The loss calculations are extended to a variable power semiconductor chip area to allow a fair comparison between the studied systems. Finally, the VIENNA 6-switches rectifier and the active filter concepts are chosen to be analysed further in Section V, where experimental tests are carried out in order to validate the proposed systems.

II. ESP System and the Line Power Quality

A. ESP Back-end Power Supply

A suitable power supply for ESP applications is depicted in Fig. 1. This topology constitutes a LCC resonant converter, which can incorporate the parasitic elements of the transformer into the circuit operation, while soft-switching features for the semiconductors persist for a wide range of operation.

The use of Variable Frequency (VF) control is

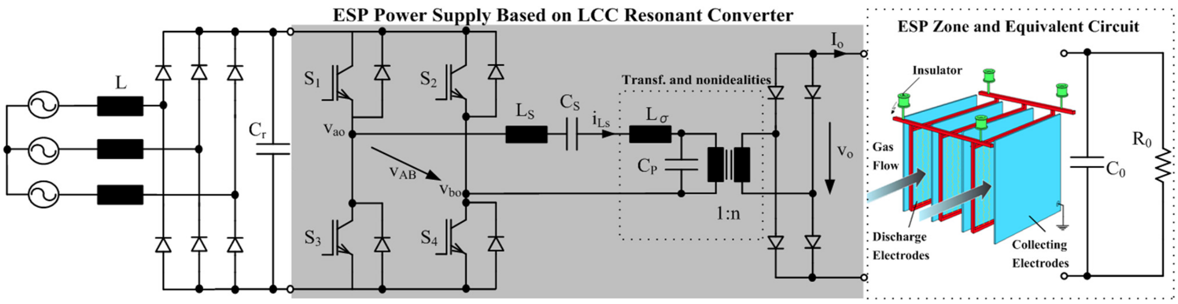


Fig. 1. Modern ESP power supply based on LCC resonant converter.

widespread in this application due to its simplicity and the naturally even loss distribution between the full-bridge switches [9]. Basically, the impedance of the resonant tank is controlled by changing the switching frequency of the inverter. While switches in one leg maintain a 50% duty cycle, the switches of the other leg are 180° phase shifted (cf. Fig. 2(a)). This commutation scheme characterizes a 2-level modulation of the inverter, where operation above resonance is desired, as the IGBTs commutate with Zero Voltage Switching (ZVS). The switches turn on when the anti-parallel diodes are conducting (ZVS turn-on) and turn off with current. Therefore, losses are generated in the turn-off process and lossless snubber capacitors are commonly employed.

One drawback of the VF control is that it normally requires a high switching frequency to reach low output current operation. Moreover, it suffers from high switching losses at high current and low output voltage operation, due to a triangular current-waveform, with turning off at the peak [9]. The large frequency variation makes it more difficult to optimize the magnetic components, gate circuitry, and the EMI filters.

Alternatively, the output power of the LCC converter can be controlled by duty-cycle variation, where the operating switching frequency is automatically adjusted to ensure that the commutation of one bridge leg takes place at zero current (ZCS) and the other bridge leg at zero voltage (ZVS) (cf. Fig. 2(b)) [9][10]. This strategy, known as Dual Control (DC), incorporates characteristics of a Phase-Shift (PS) control and of a standard VF control. Consequently, the DC control narrows the switching frequency variation in relation to the handled power, overcoming the issue of high losses in the VF control during low output power operation. A drawback of this strategy is the commonly uneven loss distribution between both legs of the full-bridge inverter. This is due to the fact that the ZCS switches are conducting current almost 50% of the switching period, while the turn-on interval of the ZVS switches is dependent on the duty cycle [10].

Fig. 2(a) and 2(b) show the main waveforms of a 60kW LCC resonant prototype operating with VF and DC controls, respectively. In these analyses the converter is fed by a 540V dc-link voltage (U_{Bus}).

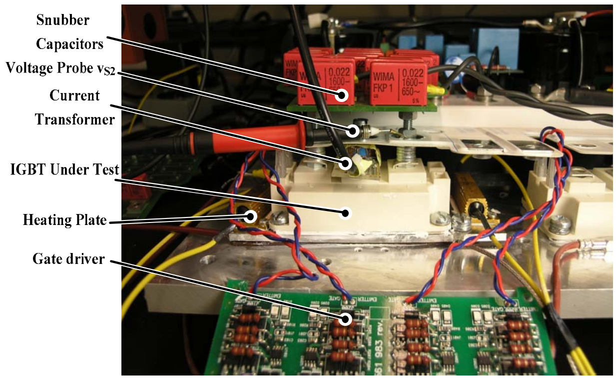


Fig. 3. Test set-up used to extract the switching loss characteristics of the IGBTs under analysis.

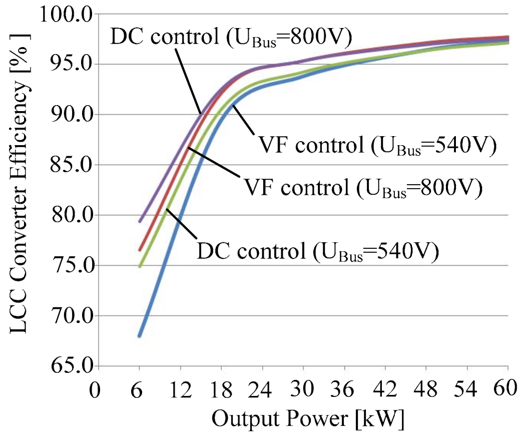


Fig. 4. 60kW LCC converter calculated efficiency for 540V and 800V dc-link voltage for VF and DC controls.

The test set-up, shown in Fig. 3, was built to experimentally obtain the switching loss characteristics of commercial power modules for different snubber capacitors such that the total power losses/efficiency of the system for any operating point could be accurately predicted. Fig. 4 shows the efficiency curves of fully designed 60kW/70kVdc LCC resonant converters employing commercial components for 540V and 800V dc-link voltages. Therein, the efficiency is calculated for different power operations, when the system is set to supply nominal current to the ESP plates. This analysis considers not only the semiconductor losses but also additional power loss sources, such as the high frequency transformer, resonant tank elements, air cooling fans,

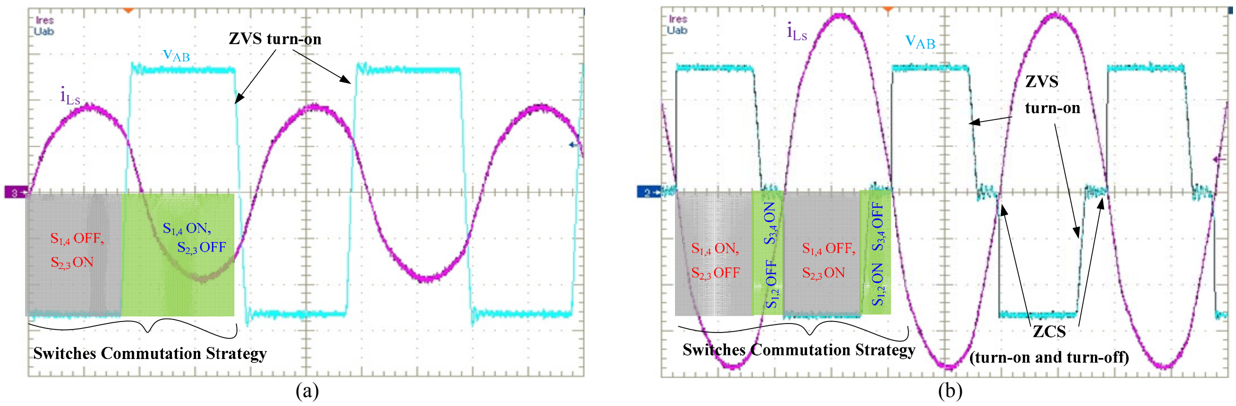


Fig. 2. 60 kW LCC resonant converter experimental results: resonant current i_{Ls} (100 A/div) and inverter output voltage v_{AB} (200 V/div) for: (a) VF control, and (b) DC control. Note that, i_{Ls} signal is inverted.

digital control and gate drives. A list of the devices used in the efficiency calculations is given in Table I.

TABLE I. LIST OF COMPONENT SELECTED FOR THE LCC CONVERTER

Component	540 V	800V
IGBTs S_1-S_4	FF300R12KE4	FF300R12KE4
Resonant Inductor L_S	25.7 µH built with arrangement of UU141/78/30	62 µH built with arrangement of UU141/78/30
Resonant Capacitor C_S	2.4 µF built with arrangement of CHJ6240	1 µF built with arrangement of CHF6100M
Parallel Capacitor C_P	120 nF	50 nF
High-Voltage Transformer	n=160 built with Vitroperm 500F	n=110 built with Vitroperm 500F
Output Rectifier	Arrangement of 3HGUF25	Arrangement of 3HGUF25

B. ESP Typical Operation Modes

An ESP can essentially operate in two different modes, named here as continuous and pulsed operation. An ESP with continuous energization operates with constant voltage in the range of 30 kVdc to 100 kVdc. Large particles and high dust loads can be dealt with effectively using this strategy. In pulsed operation, the ESP is fed with periodic high-voltage pulses in the range of 0 to 100 kVdc. This method is effective for reducing back corona and also for improving the collection efficiency of high resistivity dusts [6].

The topology presented in Fig. 1 is suitable for continuous and pulsed operations and it will be considered for further study. To illustrate the effects of the ESP energization strategies on the power quality of the mains, two 120 kW ESP power supplies built with a 3-phase passive rectifier and LCC resonant converter were tested. The resulting experimental waveforms are illustrated in Fig. 5(a) and 5(b), for continuous and pulsed operation, respectively. As can be noted, the 6-pulse system injects significant current harmonics into the power system and the supply voltage, U_R, becomes highly distorted for both operation modes. Additionally, for pulsed operation, a significantly imbalanced loading of the grid's phases occurs.

III. ESP SYSTEMS WITH IMPROVED LINE QUALITY

Alternatives to the three-phase diode bridge rectifier used as front-end converter in the ESP power supply, depicted in Fig 1, are multi-pulse and PWM rectifier topologies, and other concepts including hybrid systems and active filters. Being suitable for this high power application, boost-type converters well described in the literature are selected and discussed in this section.

A. ESP System Employing Multi-pulse Solution

3-phase transformers providing phase shift between primary and secondary windings as a multiple of 30 degrees could be employed to supply voltage to the ESP power converter. As an example, an autotransformer with differential connection, processing only about 20% of the load power, could be used to build a 12 pulse rectifier system [3]. Fig. 6 illustrates a suitable arrangement for a multi-pulse ESP power supply, where the modularization of the LCC resonant converter proposed in [8] is used to improve the power sharing between the two full-bridge inverters, as well as the power loading in the secondary windings of the transformer.

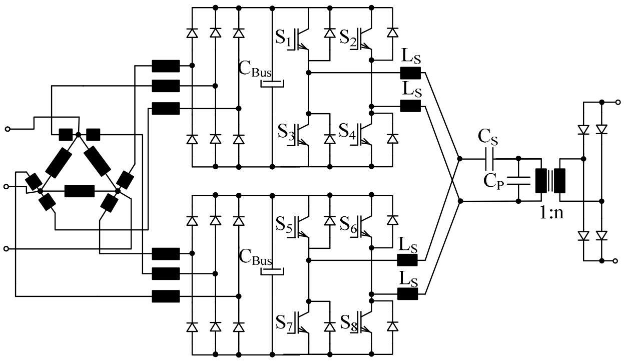


Fig. 6. 12 pulse ESP power supply.

In order to evaluate the feasibility of this solution, two ESP power supplies were tested. A Dy1 type transformer with turn ratio of √3:1 fed by a 400V line-to-line grid was utilized to feed power to one power supply unit, while the second system was directly connected to the 400 V grid. The experimental results are illustrated in Fig. 5(c).

Table II summarizes the main power characteristics of the 6- and 12-pulse systems' results shown in Fig. 5. Principally, the 12-pulse ESP power supply is appropriate to mitigate mainly the 5^{th}, 7^{th}, 11^{th} and 13^{th} line current harmonics of the conventional 6-pulse rectifier. As a result, the 12-pulse system exhibits better line power quality as it processes less reactive power. In addition, this system drains current with less harmonic distortion (THD). Finally, the 12-pulse system could deliver 20 kW more power to the ESP plates than the traditional 6-pulse

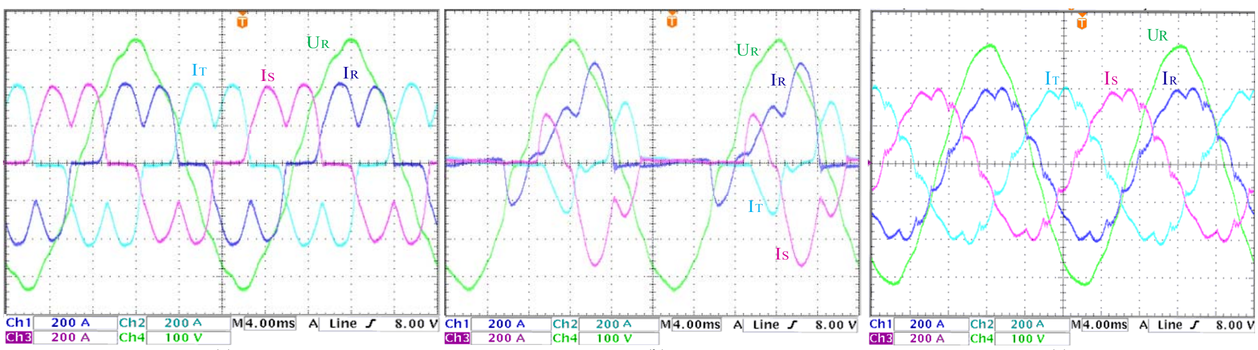


Fig. 5. Experimental results for: (a) 6-pulse ESP power supply operating in continuous mode; (b) 6-pulse ESP power supply operating in pulsed mode; and (c) 12 pulse ESP system operating in continuous mode.

system. On the other hand, the constructed 12-pulse system cannot fully fulfil mains power quality requirements, such as the IEEE 519. Therefore, additional filtering concepts would be necessary to attain unitary power factor operation.

In [11], a 3-phase unity power factor rectifier, employing 12-pulse transformer was proposed. This topology, shown in Fig. 9(d), can not only produce line currents of sinusoidal shape, but can also control the output voltage. For these reasons it will be considered for further analysis.

TABLE II. ESP SYSTEM'S LINE POWER QUALITY SUMMARY.

Characteristic	6-pulse	12-pulse
Total apparent power	195.5 kVA	192.7 kVA
ESP active power (P_o)	150 kW	170 kW
Line current THD	38%	7.4%
5th, 7th, 11th and 13th current harmonic	35%,11%,6%, 3%	1.5%,1%,6%, 2%

B. ESP System Employing PWM Rectifier

With a large potential market, tough regulations and severe economic restraints, the design of unity power factor converters operating with a low current total harmonic distortion have become a focus of attention in many industrial applications [12]. Fig. 7 shows several PWM rectifier concepts suitable for shaping the line currents and also to control the dc-link voltage [11]-[18]. The implementation of the unipolar and bidirectional switches shown in Fig. 7 can be performed with many basic switch types illustrated in Fig. 8.

By controlling the dc-link voltage, a maximum utilization of the back-end converter for a wide input voltage region can be achieved with any front-end converter based on the PWM rectifier realizations shown in Fig. 7. In addition, with the possibility of operating at a high voltage level, the losses of the back-end converter components can be reduced (cf. Fig. 4). Typically, active PWM solutions allow a 2-phase operation, increasing the reliability of the ESP system. In fact, no changes in the controller structure or parameters are required to handle a phase-loss fault condition during operation [14].

In the low-voltage converter market, where the line-to-line grid voltages range up to 690 Vrms, the 2-level rectifiers (cf. Fig. 7(a)-7(d)) are widespread. On the other hand, 3-level topologies (cf. Fig. 7(e) and 7(f)) display superior current harmonic spectra for a given switching frequency, a lower common-mode voltage and substantially lower magnetic volume than the 2-level converters. Unfortunately, the advantages of the 3-level

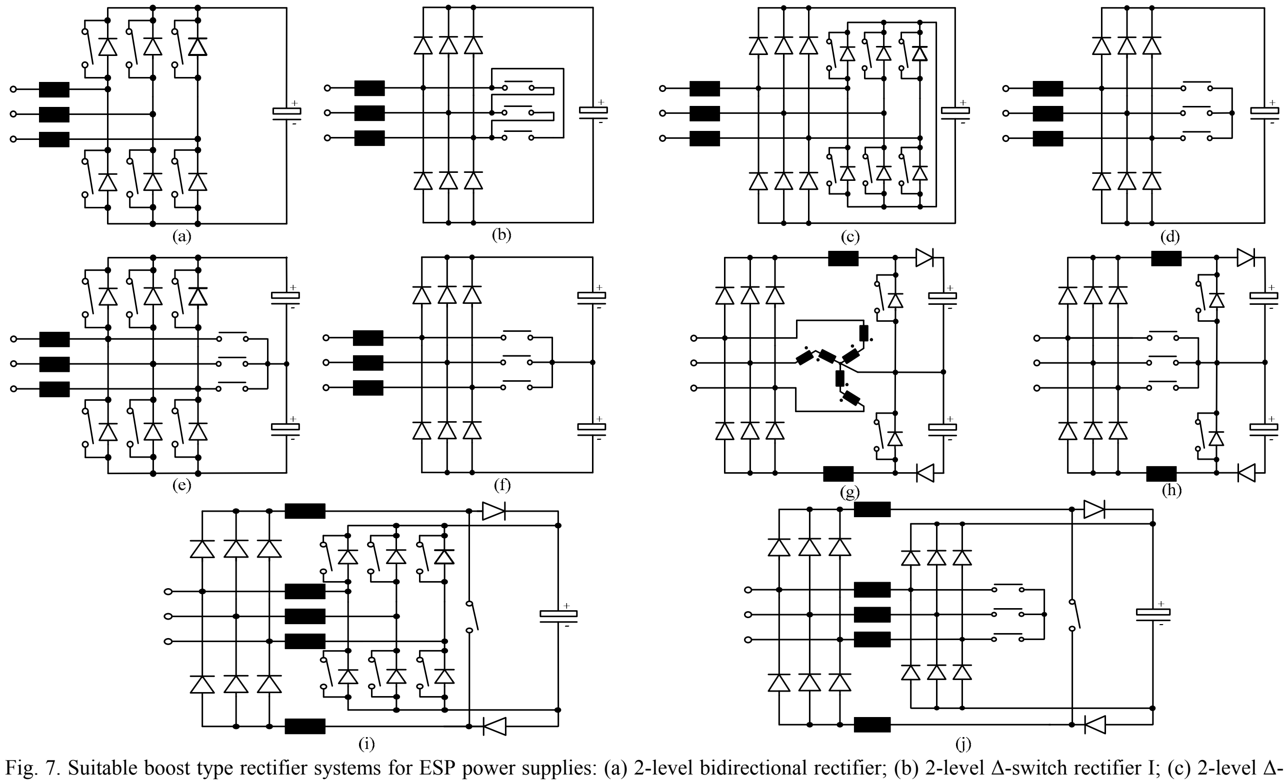


Fig. 7. Suitable boost type rectifier systems for ESP power supplies: (a) 2-level bidirectional rectifier; (b) 2-level Δ-switch rectifier I; (c) 2-level Δ-switch rectifier II; (d) 2-level Y-switch rectifier; (e) 3-level bidirectional rectifier; (f) 3-level unidirectional rectifier; (g) Minnesota rectifier; (h) active 3-phase 3rd harmonic injection into the grid phase; (i) bidirectional hybrid rectifier; and (j) hybrid Y-switch rectifier .

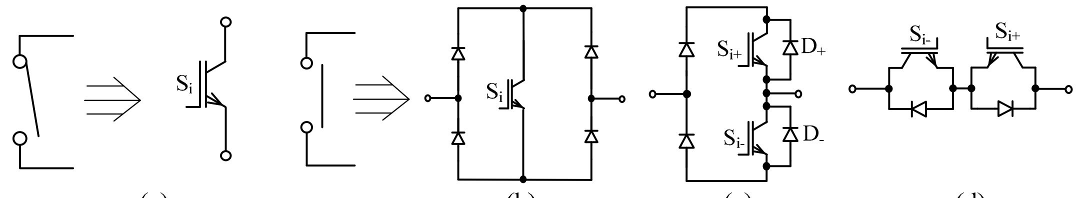


Fig. 8. Basic switch types: (a) unipolar switch; and bidirectional (current) and bipolar (voltage) switch employing (b) single active switch; (c) and (d) two active switches. Note that depends on how the switch shown in (c) is used, the diodes D_+ and D_- are not required.

systems are often obtained at the cost of increasing the number of semiconductor devices.

Fig. 7(b) to 7(d) present attractive 3-phase rectifiers, employing Δ or Y configuration of bidirectional switches on the AC terminals. The 2-level bidirectional system' issue of possible shoot-through of a bridge-leg, which would result in a short circuit of the dc-link, is overcome in these topologies. In addition, these systems do not require balancing control of the dc-link capacitor voltages, leading to a more reliable operation when compared to the 3-level systems where the active control of their neutral point potential is essential.

As can be seen in Fig. 8, a bidirectional (current) switch can be formed with one or two active switches. Essentially, during the grid voltage period, the current circulating through S_i in the single switch version is divided between S_{i+} and S_{i-} in the 2-switch versions. As a result, the total conduction and switching losses across the active switches are equal. As soon as the inductor and capacitor stresses are similar for any individual rectifier concept built with bidirectional switches using 1 or 2 active switches, it is expected that the 2-switch versions achieve higher efficiency because commonly less components exists in the current path. For instance, the original VIENNA rectifier topology, which uses a single active switch per phase leg, has higher conduction losses than the realization using two active switches. Therefore, the 2-switch based VIENNA rectifier constitutes a better solution for high power applications, but one has to accept the increased number of gate drive circuits.

In this work, among the PWM boost type technologies shown in Fig. 7, the 2-level bidirectional VSC, the high efficiency 3-level VIENNA rectifier 6-switch version, and the Δ-switch rectifier I are selected for further evaluation. These topologies are shown in Fig. 9(a), 9(b), and 9(c), respectively.

C. *ESP Systems Employing Hybrid Rectifier*

Hybrid rectifiers are commonly formed by a combination of passive and active systems. A classical example is the Minnesota rectifier shown in Fig. 7(g) [15]. Using a zig-zag transformer to inject a 3rd harmonic triangular current into the grid phases, a purely sinusoidal shape of the line currents can be achieved. Alternatively, the zig-zag transformer could be replaced by other passive networks or by a star-connected bidirectional switch as shown in Fig. 7(h).

Hybrid rectifiers can also be formed by the series and/or parallel connection of a line-commuted rectifier and a self-commuted converter [16]. These systems aim to take the advantage of the commonly low power losses and high reliability of a diode based rectifier and also benefit from the PWM rectifier capability of processing reactive power. Therefore, a highly efficient rectifier system with controlled dc-link voltage, capable of providing close to sinusoidal shaped line current can be assembled. In general, the usually highly efficient system is set to operate with low frequency, processing the highest power rating, while the PWM system is adjusted to work at higher frequencies and lower power rating.

Fig. 7(i) and 7(j) show suitable hybrid systems comprising two active rectifiers, one based on a 3-phase active boost and the other one chosen from the PWM 2-level rectifiers illustrated in Fig. 7(a) and 7(d), respectively. Interestingly, in case of failure of one of the active rectifiers, the other working structure can continue delivering power at controlled dc-link voltage. For ESP systems with multiple power supplies, the hybrid concept shown in Fig. 7(j) is preferable because even when its load is not draining power, working like an active filter, the bidirectional VSR can still shape the line currents of the other power supplies. Thus, the topology illustrated in Fig. 9(e), using a dual active boost to lower the effective switching losses, is chosen for further evaluation.

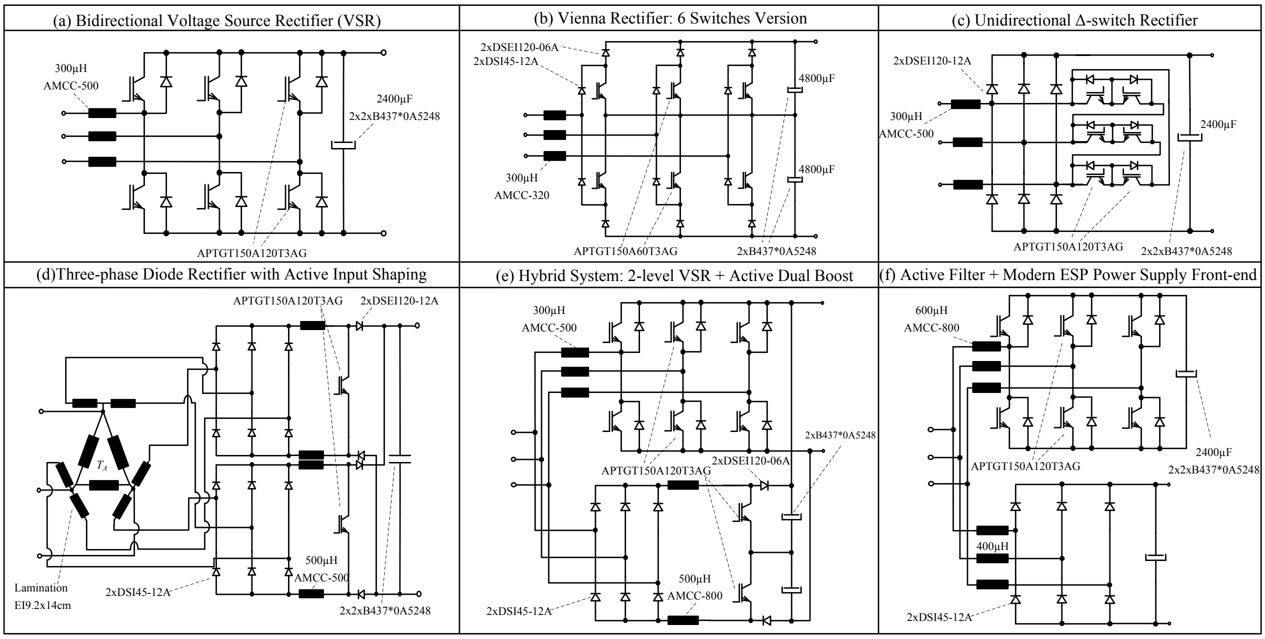


Fig. 9. ESP power supplies with low effect on the mains employing as front-end converter: (a) 2-level bidirectional voltage source rectifier; (b) VIENNA rectifier: 6-switch version; (c) 2-level Δ-switch rectifier; (d) 3-phase unity-power factor diode rectifier with active input shaping; (e) Hybrid rectifier employing 2-level bidirectional VSR and active dual boost; and (f) shunt active filter solution.

D. ESP System Employing Shunt Active Filter Solution

In order to improve the line power quality of the ESP system depicted in Fig. 1, a shunt active filter (AF) can be employed as presented in Fig. 9(f). This solution is very attractive because the reliability of the ESP power supplies based on passive rectifiers is preserved [3]. On the other hand, the active filter usually needs to process high amounts of reactive power to allow line currents of sinusoidal shape (40% to 60%).

IV. Comparative Evaluation

In order to identify suitable systems for ESP applications, each one of the concepts presented in Fig. 9 is fully designed employing commercial components for a defined power capability of 60 kW and switching frequency of 20 kHz. A 800 V dc-link voltage is specified for each studied topology, when a 400 V line-to-line 50 Hz 3-phase input voltage is considered.

Table III shows a summary of the line power quality performances obtained with each designed system, which include: the achieved maximum power density of the Front-end converter ρ_F, the power factor λ, the total harmonic distortion of the line currents $THDi_A$ (up to 40^{th} harmonics), the total η, and partial efficiency for the front-end η_F, and back-end topologies η_B, magnetic rated power S_L, and capacitor current stress I_C. For any system, these characteristics can give information of size/volume, costs of components, energy savings, ability to meet power quality requirements, and so forth.

The power losses from the semiconductors are determined directly in the circuit simulator. The instantaneous current, which passes through the semiconductor, is combined with the conduction and switching loss characteristics by a 2^{nd} order equation using fitted coefficients obtained by data-sheets. The current stress across the capacitor, I_C, is determined by the ratio between the rms values of its current and the rectifier output current. The rated power of magnetic components, S_L, is evaluated as in [15], in such a way that the inductors are characterized by the rated power of an equivalent transformer. Finally, the maximum power density, ρ_F, is obtained by dividing the total power processed by the total volume of the designed front-end converter. The total volume is calculated by adding up the volume of each selected commercial component.

All the analyzed systems can operate with close to unitary power factor, exhibiting very low harmonic content in the input current. The solutions that can control the dc-link voltage are especially interesting due to the fact that a maximum utilization of the back-end converter for a wide input voltage region can be obtained.

For the hybrid rectifier shown in Fig. 9(e), the active boost structure is set to operate at the same switching frequency of the 2-level rectifier (20 kHz), however it is set to process about 70% of the load power. This solution can increase the reliability of the ESP system operation if both active structures are designed to cope with 100% of the load power, but the system becomes very costly. In order to increase the system efficiency the active boost structure could be set to operate at relatively low switching frequency handling about 80% of the load power.

The active filter solution is the only one which does not control the output voltage of the front-end converter. Additionally, the active filter needs to process high amounts of reactive power to allow sinusoidal shape of the line currents. However, this concept is very interesting, as the reliability of the ESP power supplies based on passive rectifiers is preserved.

The solution depicted in Fig. 9(d) is considerably heavy and bulky as it employs a transformer processing about 20% of the load power. The efficiency achieved is relatively low, and unfortunately, sinusoidal line currents are only obtained during constant power load operation. Due to these drawbacks, this system is not considered for further analysis.

The system employing the VIENNA rectifier has the best combination of features among the analyzed structures. Due to the relatively low semiconductor losses and low rated power of the inductive components, this solution can achieve the highest power density and efficiency.

Especially for high switching frequencies, the Δ-switch rectifier demonstrates considerably better efficiency than the 2-level bidirectional rectifier. This is mainly because the Δ IGBTs only commutate during 120^0 of the fundamental grid period against the always 180^0 of the bidirectional solution. Hence, the Δ-switch rectifier naturally has lower switching losses. However, at 20 kHz, the VIENNA rectifier constitutes a better solution.

A. Chip Area Based Comparison and Discussion

For a fair comparison between all proposed ESP power supplies, the chip sizes of each system could be adapted for a given operating point such that the maximum or average IGBT and diode junction temperatures, $T_{J,T/D}$, are equal or less than a predefined maximum value, e.g. $T_{J,max}=125^oC$. This strategy not only guarantees optimal chip area partitioning and semiconductor material usage,

TABLE III. Summary of the calculated features of the designed ESP systems

Component	2-Level Bid.	VIENNA Rect.	Δ-Switch Rect.	3ϕ Act. Inp. S.	Hybrid Rect.	Act. Filter (AF)
power factor λ	99.8%	99.8%	99.8%	99.7%	99.6%	99.7%
front-end converter power density ρ_F	2.4 kW/dm^3	4 kW/dm^3	2.4 kW/dm^3	1.1 kW/dm^3	2.3 kW/dm^3	2.6 kW/dm^3
$THDi_A$	1.9%	2.1%	2.0%	3.3%	7.2%	2.5%
front-end converter efficiency η_F	95.7%	97.6%	96.9%	96.0%	96.7%	97.1%(AF)/ 99.2% (Pass. Rect.)
LCC resonant converter efficiency η_B (VF control)	98.0%	98.0%	98.0%	98.0%	98.0%	97.6%
total efficiency η	93.7%	95.7%	95.0%	94.1%	94.8%	94.0%
magnetic rated power S_L	1.9%	0.9%	1.9%	21.0%	1.8%	4.0%
capacitor current stress I_C	71%	71%	71%	59%	53%	99%

but also provides a common basis for comparisons [17].

Due to their good documentation and data availability, the Infineon Trench and Field Stop 1200 V IGBT4 and 600 V IGBT3 series have been chosen as the data basis. With a statistical analysis of many commercial devices, datasheets and manufacturer data, the power losses and thermal characteristics of these semiconductor series can be modelled with a chip die size, $A_{S,T/D}$. A detailed description of the employed chip area optimization, including the resulting expressions for the IGBTs and diodes power loss and thermal characteristics modelled with a nominal chip area, are given in [17] and [18].

In this work, using the derived chip area mathematical expressions, the optimization algorithm calculates the losses of each topology and chip sizes until the average junction temperature of each semiconductor chip reaches T_J=125°C, assuming a heat sink temperature of T_{Sink}=80°C. By summing up all optimized chip sizes, the total chip area, the semiconductor costs and the total efficiency for a topology and corresponding operation point can be found.

Fig. 10 shows the silicon area optimization results for most of the 60kW ESP front-end concepts depicted in Fig. 9. Therein, the total chip area is calculated depending on the switching frequency. For the hybrid rectifier the active boost structure is set to operate at the same switching frequency as the 2-level bidirectional rectifier, but delivering about 70% of the load power.

The area increase with the switching frequency is lowest for the 3-level VIENNA rectifier, because of the intrinsically small increase in switching losses. The total chip area of this rectifier is already lower than any other studied solution for switching frequencies above 6 kHz. Consequently, the total cost of the semiconductors in a VIENNA rectifier can be expressively lower, especially for high switching frequencies. For instance at 25 kHz, the necessary chip area of the VIENNA rectifier is about 1.7 times lower than the 2-level bidirectional VSR and 1.3 times lower than the area of the Δ-switch rectifier.

Interestingly, among the concepts employing a 2-level bidirectional VSC, the active filter has the best performance for frequencies above 12 kHz. Between 5.5 kHz and 12 kHz the hybrid solution is superior. Finally, the conventional 2-level VSC is only a better solution for very low switching frequencies.

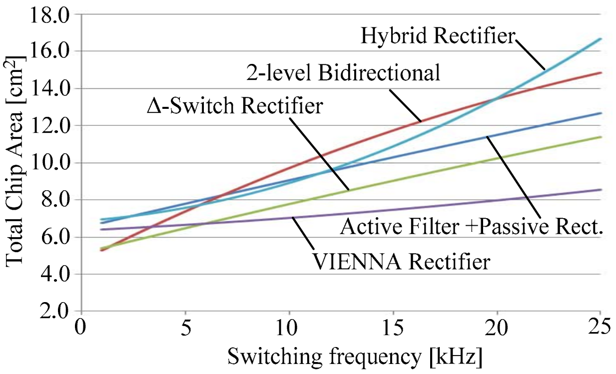


Fig. 10. Comparison of the total semiconductor area of 60 kW ESP front-end converter concepts.

V. ESP Systems Experimental Evaluation

In this section, the feasibility of the VIENNA rectifier and active filter concepts for ESP applications are demonstrated.

A. *ESP System Employing Shunt Active Filter Solution*

A shunt active filter was installed in the ESP test set-up evaluated in Section II-B to further improve the line power quality of this system. The obtained experimental result is depicted in Fig. 11. Note that the active filter processes a high amount of reactive power (47% of the 82 kW of the load power) to allow sinusoidal shape of the line currents ($THDi_R$ = 4.6%). Alternatively, the active filter could be set to only compensate current harmonics to shape the line currents, without then correcting the displacement factor. In this way, the rated reactive power processed would be reduced to 43% (cf. Fig. 11(b)).

In case the active filter was installed in a 12-pulse ESP system, the reactive power processed by this active solution would be considerably smaller. Fig. 11(c) presents the experimental result for a 12-pulse ESP system processing about 148 kVA, operating with a shunt active filter. As can be seen, a very low harmonic content in the input current can be achieved ($THDi_R$ = 2.8%). In this test condition, the active filter processes the amount of reactive power of only about 9.5% of the load power.

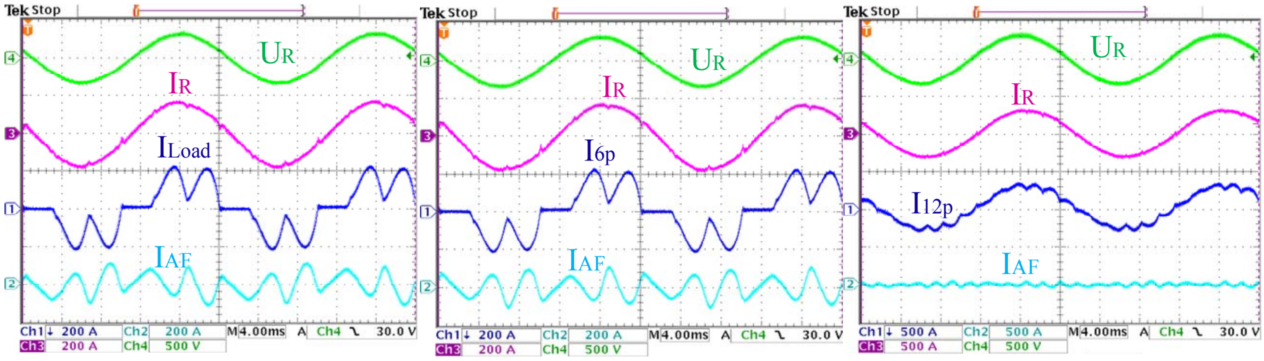
B. *ESP Power Supply Employing VIENNA Rectifier*

In order to verify the feasibility of the VIENNA 6 switches rectifier for ESP application, a 12 kW/72 kHz prototype was tested (cf. Fig. 12(a)). The power density of this active rectifier is 4.6 kW/dm^3. The total system efficiency for nominal operation is around 97.6%.

In Fig. 12(b) the line current and voltage of phase R for operation at 10.5 kW are shown. A system with a high power factor, including balanced mains phases loading and very low harmonic content in the input currents can be achieved ($THDi_R$ = 2.8%). In Fig. 12(c) the results of an output power transient from idle (0 kW) to 4 kW operation, emulating a pulsed operation, is presented. For this test condition the control of the system could effectively balance the voltage shared between the dc-link capacitors, shaping the line currents as desired. The results verify the feasibility of the VIENNA rectifier for ESP applications.

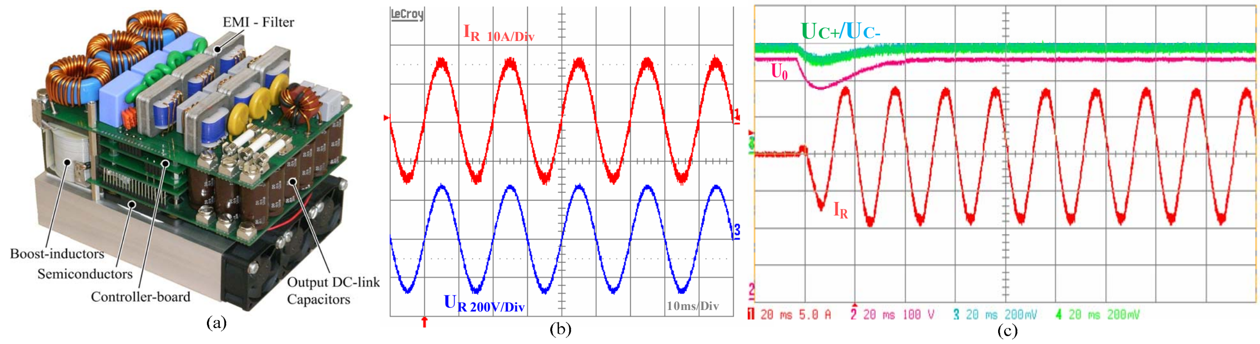
VI. Conclusions

In this work suitable power supplies for ESP applications are proposed. Multi-pulse and PWM rectifier topologies and other concepts including hybrid systems and active filters are investigated as replacements for the 3-phase diode bridge rectifier which is commonly used as front-end converter in modern ESP power supplies. A comparison of the studied systems rated to 60 kW and fully designed employing commercial components is shown. The ESP systems' efficiency, power density, current harmonic THD, among other qualities, are used for the assessment. The loss calculations are extended to a variable chip area to allow a fair comparison between the studied systems. Finally, the VIENNA 6-switches



(a) (b) (c)

Fig. 11. Experimental results for ESP systems employing active filter: 6 pulse ESP system + active filter operating (a) with and (b) without displacement factor compensation; and (c) 12 pulse ESP system + active filter without displacement factor compensation. .



(a) (b) (c)

Fig. 12. Experimental results for ESP systems employing active rectifiers:(a) 12kW VIENNA rectifier prototype; (b) Line current I_R and voltage U_R of the phase R for operation at 10.5kW; and (c) dc-link capacitor voltages U_{C+}/U_{C-} , output voltage U_0, and line current of phase R I_R for load step of 0 kW to 4 kW.

rectifier and the active filter concepts were chosen to experimentally verify the study. The results verify the feasibility of the selected systems for ESP applications.

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