

# Comparison of Concepts for Improving the Line Power Quality of Electrostatic Precipitator Systems

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**Abstract**— In this article the distortions caused by the pulsed operation of a group of power supplies (PS) feeding an Electrostatic Precipitator (ESP) are investigated, and means for improving the line power quality are proposed. In order to reduce the Total Harmonic Distortions (THD) of the line current and also to improve the loading balance between the grid phases for pulsed operation, the pulses of the individual power supplies are scheduled and controlled together, so that the power consumption becomes more continuous. As an alternative to the three-phase diode bridge rectifiers, which are used as front-end converters in modern ESP power supplies, multi-pulse and PWM rectifier topologies described in the literature and other concepts including hybrid systems as well as active filters are evaluated in order to identify a suitable topology for ESP applications. A comparison of the proposed ESP systems, considering the implementation complexity, power semiconductor losses, circuit elements stresses, etc. is presented.

## I. INTRODUCTION

Due to increasing concerns about environmental pollution, the reduction of particle emissions by Electrostatic Precipitators (ESPs) is a highly important issue for coal-fired power plants [1]. ESPs are highly suitable, reliable and robust dust collectors. Moreover, they are very efficient, as degrees of separation above 99.9% can be achieved. When compared with fabric filters, their operating costs are low and the risk of damage and stoppage owing to functional disorders is considerably smaller [1].

Industrial ESPs are normally divided into several sections in order to increase their collection efficiency [2]. Each of these sections has its own power supply (PS), which is controlled individually and has a typical output power range of 10kW to 120kW and an output voltage range of 30kV<sub>DC</sub> to 100kV<sub>DC</sub> [3]. These power supplies can have different converter topologies or configurations, depending on their location within the ESP [2]. In middle and outlet fields, for example, pulsed voltages are used more and more frequently, as they increase the collection efficiency of fine particles. A typical ESP electrical installation is depicted in Fig. 1, where due to the large number of ESP sections and the high power processed, a dedicated substation, with two or more distribution transformers is commonly used.

Modern power supplies for ESPs are based on resonant converters in order to utilize the transformer's parasitics and to have soft switching for a wide operating range [3], [4]. Fig. 2 shows a possible circuit diagram for an ESP power supply (cf. [1] and [3-6]). This topology uses modularization by

cascading resonant converters in order to increase the power capability of the system [5]. As can be observed, this system employs a three-phase diode bridge rectifier as a front-end converter due to its simplicity, reliability and low cost [3-6]. The main drawback of this concept is that diode rectifiers inject significant current harmonics into the power system which could overload the nearby shunt capacitors, or distort the mains voltage at the point of common coupling. Therefore, simple rectifiers do not meet the IEEE 519 guidelines concerning input current harmonics. Especially in pulsed operation, a drastically imbalanced loading of the mains phases could occur. Accordingly, the concept employed today bears the risk of causing severe problems, such as malfunction of other equipment fed by the same mains, audible noise, increased losses of transformers, generators and power lines, electric resonances in the mains, and mechanical oscillations in generators.

In order to fulfil mains power quality requirements, e.g. IEEE 519, the overall influence of the multiple three-phase rectifier supplies of an ESP on the mains current is studied in this article and new control concepts for minimizing the effects on the mains without impairing the ESP collection efficiency are proposed. Section II aims towards a better

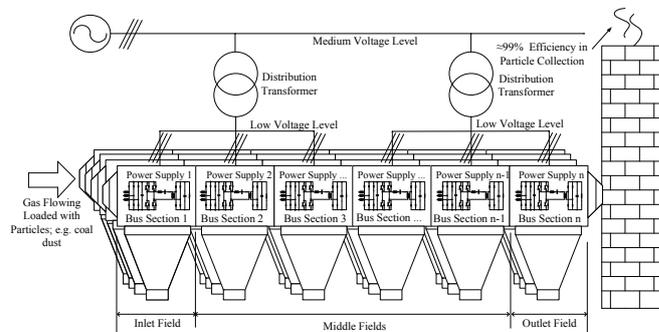


Fig. 1. Typical ESP installation scheme of a system with 24 power supplies.

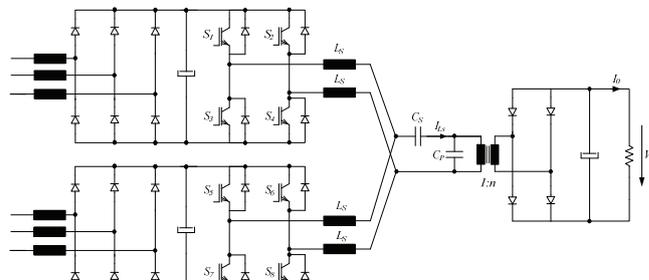


Fig. 2. ESP power supplies based on series-parallel resonant converters.

understanding of the interaction between the ESP's power supplies and the mains, taking into account the power supply as such, as well as the system of power supplies feeding an ESP with special attention to pulsed operation.

As a replacement to the three-phase diode bridge rectifiers, multi-pulse and PWM rectifier topologies described in literature and other concepts including hybrid systems comprising passive and active rectifiers as well as active filters are evaluated in Section III, in order to identify suitable systems for ESP applications. Furthermore, new control modes and new topological arrangements for groups of power supplies, inherently correcting any imbalance caused by the ESP's operation modes, are studied and solutions such as a high power DC vs. AC power distribution systems are analyzed. In Section IV, a comparison of the studied ESP system, considering the implementation complexity, power semiconductor losses, circuit elements stresses, etc. is presented.

## II. ESP SYSTEM AND THE LINE POWER QUALITY

In this section, the energization characteristics of ESP systems are presented. In addition, the interaction between the mains and a group of power supplies feeding an ESP system is investigated.

### A. Characteristics of an ESP system

Typically, an ESP with conventional energization operates with constant voltages in the range of 30 kV<sub>DC</sub> to 100 kV<sub>DC</sub> [3]. Large particles and high dust loads can be addressed effectively using this energization (characteristic of the Inlet Field). Frequent flashovers happen in this operation mode and a de-ionization time is needed to prevent repetitive sparks [2]. A flashover occurs when the flowing gas dielectric of the ESP breaks down, this results in a short-circuit of the power supply output.

In pulsed operation, the ESP is fed with periodic high-voltage pulses in the range of 0 to 100kV. This method is effective for reducing back corona, improving the collection efficiency of high resistivity dusts, whilst reduces energy consumption [2]. The pulse width (PW) usually ranges from 1ms to 10ms and the repetition rate from 1Hz to 100Hz.

The topology presented in Fig. 2 is suitable for both energization modes.

### B. ESP Power Supply Effects on the Line Power Quality

To illustrate the effects of the ESP energization strategies on the power quality of the mains, simulation of a 60kW high output voltage resonant converter fed by diode-based three-phase mains rectifiers has been performed (cf. Fig. 2). The electrostatic precipitator was modelled by the parallel connection of an electrical resistance and a capacitor as shown in Fig. 2 [2]. The basic waveforms obtained with the simulations are illustrated in Fig. 3 for continuous operation with and without flashovers, and with pulsed operation.

As can be observed in Fig. 3(a), the line currents drained by the power supply operating with continuous energization are normally balanced presenting harmonics of the order  $n = (6.i \pm 1)$ , where  $i \geq 1$ . However, to completely understand the effects of the conventional energization on the mains, the

possibility that a flashover happens needs to be taken into account. To simulate this phenomenon the output of the converter shown in Fig. 2 was short circuited during 10ms and then the system returned to normal operation. Note that the occurrence of flashovers depends on some parameters, (e.g. dust load of the zone and its electrical field strength) which is hard to predict [2]. As soon as a flashover happens the dc link voltage increases due to the sudden reduction of the power consumption. As a consequence, a reduction of the diode's current conduction takes place, where in most of the cases, this results in complete blockage of this semiconductor. Imbalance in the power loading of the mains, higher voltage distortions and average value in the line currents can be caused (cf. Fig. 3(b)).

In pulsed operation, the line currents are normally imbalanced and highly distorted (cf. Fig. 3(c)). The power balance on the mains can become critical, as high line current peaks may appear when the pulses are released, and almost no current is required with no pulse. These effects are due to the voltage variation of the load, which causes a low frequency disturbance in the bus-bar capacitor voltage.

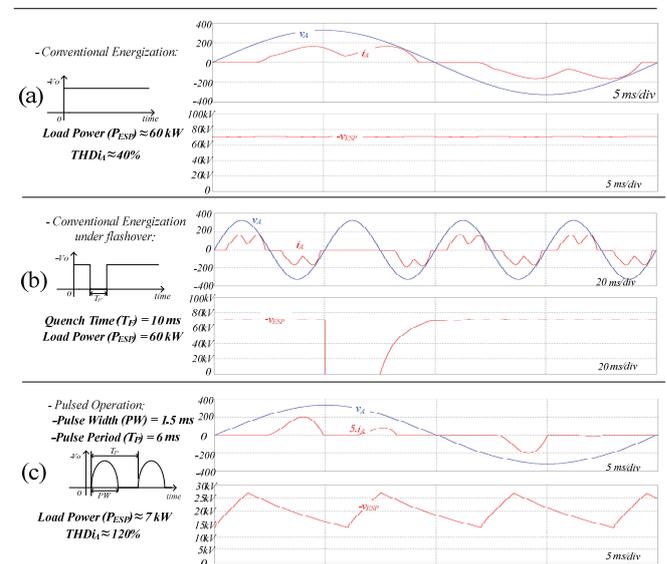


Fig. 3. ESP energization techniques: (a) Conventional energization; (b) Conventional energization with flashovers; and (c) Pulsed operation.

## III. ESP SYSTEMS WITH IMPROVED LINE QUALITY

In this section, a strategy to solve the inherit problems caused by pulsed operation is shown, where the main idea is to arrange the systems pulses in an optimal sequence, so that the group of pulsed power supplies has similar line behaviour to that which an equivalent single power supply operating in continuous mode, would have.

Alternatives to the three-phase diode bridge rectifiers used in ESP power supplies depicted in Fig 2 are multi-pulse and PWM rectifier topologies and other concepts including hybrid systems and active filters, which are summarized in Fig. 4. In the following, these concepts are discussed and evaluated for a typical ESP installation comprising 16 power supplies operating in pulsed mode, with pulse configuration shown in Fig. 5. Therein, all the power supplies are fed by the same mains.

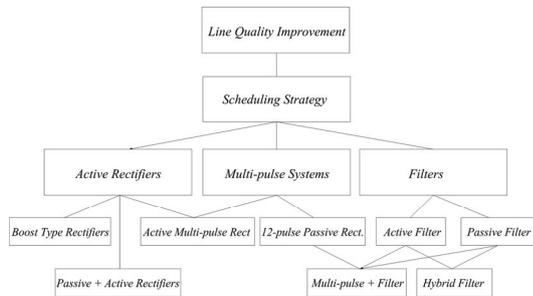


Fig. 4. Concepts for improving the line power quality in ESP systems.

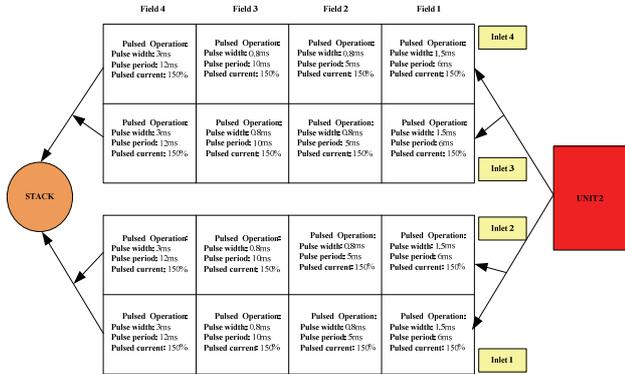


Fig. 5. Arrangements and the pulse parameter settings for an ESP system with 16 pulsed power supplies.

#### A. Pulse Optimization Using Scheduling Strategy

In [7], two methods to solve the inherit problems caused by pulsed operation were proposed. The first method (OS) uses the time domain sampled-data model of the analyzed ESP system for determining the optimal set of pulse parameters, which results in minimal Total Harmonic Distortion (THD) of the line currents when controlling the ESP supplies. The second method (ES) presents an algorithm which schedules pulses to fill the gaps between a pulse reference and the pulses of the other power units, so that the system's power consumption becomes more continuous.

The performance of ES pulse optimization strategy proposed by [7] for up to eight power supplies operating with pulse width of 3ms and period of 12ms is shown in Fig. 6. Therein, the line current waveforms obtained for each different group of power supplies optimized are shown. As can be noted, the more pulsed power supplies being optimized, the more similar the line currents are to the ones which a system with continuous operation would have.

In order to verify the improvement in line power quality of the pulsed ESP system depicted in Fig. 5, by using the scheduling of pulse control strategy proposed by [7], the following operation conditions are investigated:

- The "Critical Case": The pulsed power supplies of the system operate without pulse control. Fig. 13(a) shows the simulation results;
- The "Optimized Case": The pulsed power supplies of the system were optimized according to the algorithm of the pulse scheduling strategy proposed by [7]. Fig. 13(a) shows the simulation results (Bottom figure);

As can be observed in Fig. 13(a), the optimized system has similar behaviour to a group of power supplies operating in

continuous mode. The line currents are balanced with harmonic distortion significantly improved compared to the "Critical Case" (cf. Fig. 13(a) upward figure). The system still generates low frequency line current harmonics with high amplitudes, mainly the 5<sup>th</sup> and 7<sup>th</sup> order harmonics, which do not comply with IEEE 519 guidelines. For the "Critical Case", line current with peaks of up to two times higher than for the "Optimized Case" can be seen.

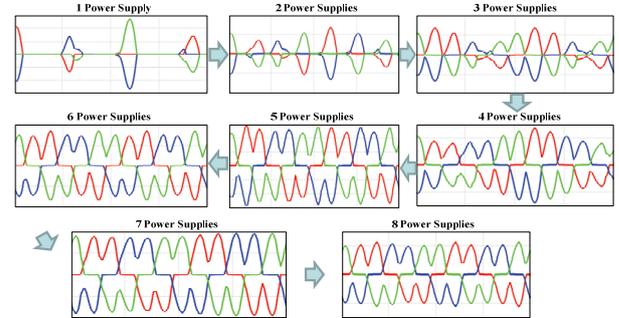


Fig. 6. Scheduling of pulses applied to different number of pulsed power supplies operating with pulse width of 3ms and period of 12ms.

#### B. ESP System Employing Multi-pulse Solutions

In the typical ESP electrical installation depicted in Fig. 1, 3-phase transformers providing phase shift between primary and secondary windings as a multiple of 30 degrees could be employed to feed the ESP's power supplies in a three-wire system. Therefore, a multi-pulse system can be built by selecting suitable distribution transformers, where the simplicity and reliability of ESP power supplies are preserved. However, the performance of a multi-pulse system strongly depends on the load balance between the secondary sides of the transformers, which could be difficult to achieve in an ESP system, as the ESP loading can vary considerably.

In order to overcome problems with the load balance of the multi-pulse transformer, the ESP system could take advantage of the modularization by cascading of converters [5] (cf. Fig. 2) to make each unit operate as a 12 pulse rectifier as shown in Fig. 7(a). This system can preserve the multi-pulse characteristics of the line currents, even when some of its power supplies suffer from flashovers as presented in Fig. 7(b), where two power supplies were operating in continuous mode and a flashover suddenly takes place in one of the ESP bus sections. Note that, as presented in Section III A, ESP systems operating in pulsed mode can display behaviour very similar to continuous operation. Therefore, they could also take advantage of the proposed multi-pulse system if the scheduling strategy is used.

For the ESP system studied here (cf. Fig. 5), only one MV/LV transformer delivers power to the system. Therefore, a LV transformer with differential connection, processing only about 21% of the load power, is used to build a 12 pulse rectifier system in order to mitigate mainly the 5<sup>th</sup> and 7<sup>th</sup> line current harmonics. The ESP power supplies with modularization by cascading (cf. Fig. 2) are used to improve the load sharing between the secondary windings of the transformer. A diagram of the proposed system is shown in Fig. 8. Fig. 13(b) presents the simulation results of the

analyzed system. As can be observed, low harmonic content of the input current can be achieved (THD=13.1% for up to 25<sup>th</sup> harmonics). The reliability and low complexity of the typical ESP installation are preserved. As this solution employs a multi-pulse transformer processing a high amount of power, the system becomes heavy, expensive and bulky.

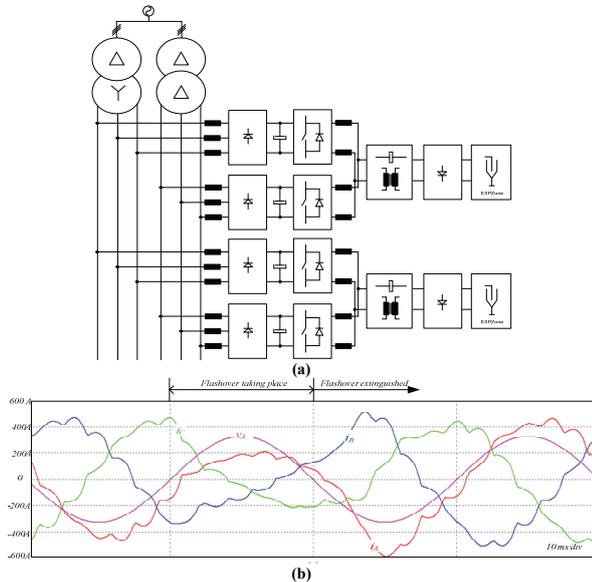


Fig. 7. 12 pulse ESP system: (a) ESP system arrangements using typical electrical installation and modern power supplies; and (b) Mains' phase current and voltage for system under flashovers.

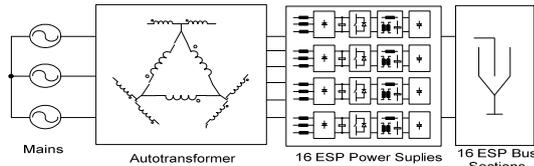


Fig. 8. 12 pulse ESP system

### C. ESP Power Supply Employing Active Rectifiers

Due to the relatively low losses across the semiconductors and low rated power of the inductive components, the Vienna 6 switches system, depicted in Fig. 9, constitutes a very good alternative to the three-phase diode bridge rectifiers [8]. This topology can obtain very low harmonic content of the input current. By controlling the bus bar capacitor voltage, a maximum utilization of the back-end converter for a wide input voltage region can be achieved. With the possibility of operating at a high voltage, the losses and volume of the back-end converter components can be reduced. In addition, this active solution allows a two-phase operation [8].

In order to evaluate the performance of the ESP power supply employing a Vienna rectifier, a 120kW unit was designed and simulations were performed for typical ESP energization. The simulation result for pulsed operation is presented in Fig. 10. By analyzing these results, it can be noticed that the proposed ESP power supply based on Vienna rectifier converter has outstanding performances when faced with this critical energization.

The simulation result for the ESP system depicted in Fig. 5, fully operating with active front-end rectifiers, is presented in Fig. 13(c). A system with balanced mains phases loading

and also very low harmonic content of the input currents (4.02%) can be achieved.

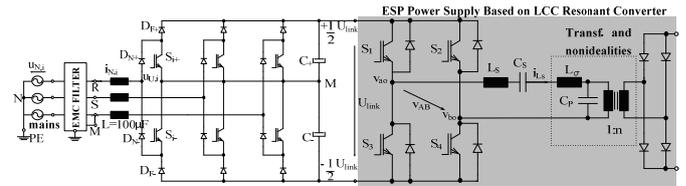


Fig. 9. ESP power supply based on Vienna rectifier.

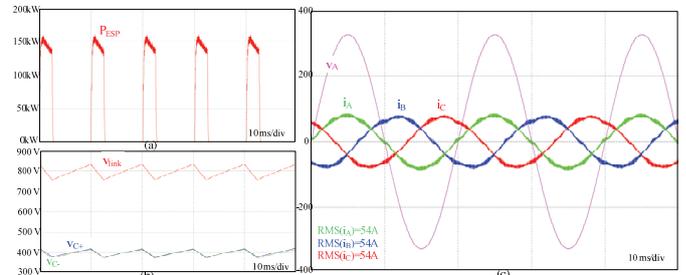


Fig. 10. Simulation results for pulsed operation with pulse period of 10ms and pulse width of 2.5ms: (a) Power delivered to the ESP plates; (b) Rectifier stage output voltages; and (c) Mains' currents and voltage.

### D. ESP System Employing Shunt Active Filter Solution

To further improve the line power quality of the system depicted in Fig. 5, a shunt active filter (AF) can be employed as presented in Fig. 11. The simulation results for this solution are depicted in Fig. 13(d). The active filter processes a high amount of reactive power (68% of the load power) to allow sinusoidal shape of the line currents (THD = 2.1% for up to the 25<sup>th</sup> harmonics). Alternatively, the active filter could be set to only compensate current harmonics to fit the line current, without then correcting the displacement factor. In this way, the amount of reactive power processed would be considerably reduced, increasing the system efficiency. The reliability of the ESP power supplies based on passive rectifiers is preserved.

### E. ESP System Employing Shunt Active Filter and Multi-pulse Solution

An ESP system with high line power quality can be derived combining a shunt active filter and a multi-pulse transformer. To obtain high efficiency, an autotransformer with differential connection, processing only about 21% of the load power, is used to build the 12 pulse rectifier. In addition, the ESP power supplies with modularization by cascading of converters (cf. Fig. 2) are used to improve the load balance in the transformer secondary side. In addition, a shunt active filter is installed on the primary side of the autotransformer. The simulation result for the proposed solution is presented in Fig. 13(e). As can be seen, a very low harmonic content of the input current can be achieved (THD = 1.48%). Due to the fact that this solution employs a multi-pulse transformer processing a high amount of power, the system becomes heavy, expensive and bulky. To allow a system with resistive mains frequency behaviour, the active filter needs to process the amount of reactive power of only about 19.2% of the load power. This increases the efficiency of the system considerably, whilst preserving its reliability.

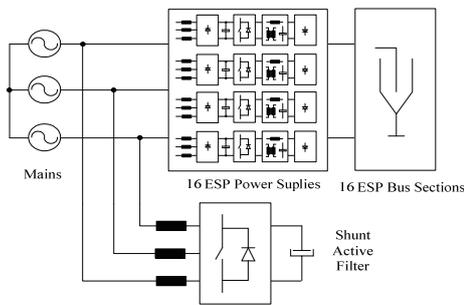


Fig. 11. ESP system employing a shunt active filter.

#### F. DC Distribution Systems

A DC distribution system is designed to deliver power to the 12 back-end converters of the system depicted in Fig. 5. Any rectifier topology suitable for an ESP front-end converter could be used. In this study, as illustrated in Fig. 12, a hybrid system comprising a bidirectional voltage source rectifier and an active boost was selected in order to increase the system reliability. Thus, in case of failure of one of the active rectifiers, the other working structure can continue delivering full power to the ESP system. The total cost of the structure becomes high as each active rectifier is designed to cope with full load power. In order to increase the system efficiency, the bidirectional structure is set to process active power of only about 20% of the load required power, whilst the active boost delivers the others 80%. The simulation results for the designed DC distribution system are shown in Fig. 13(f). As can be observed the system achieves relatively low harmonic content of the input currents (THD= 7%). This system presents the lowest reliability among the analyzed systems. However, parallelism of converters could be employed to increase the system reliability.

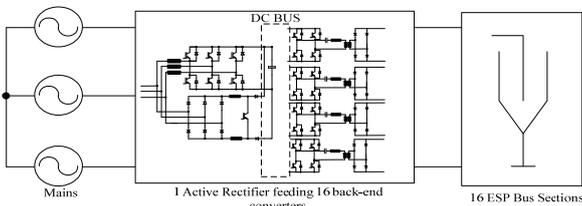


Fig. 12. DC distribution system based on a hybrid rectifier delivering power to 16 back-end converters.

#### IV. ESP SYSTEMS COMPARATIVE EVALUATION

This section provides a comparison of the proposed ESP systems regarding realization effort, stresses on the components, etc. The evaluation criteria, characteristic quantities and definitions are similar to the one presented in [9], where three-phase rectifier systems were investigated.

In order to determine the ESP systems' efficiency, each system was fully designed employing commercial semiconductors, capacitors and magnetic elements. The power losses from the semiconductors were predicted according to [10], where the total losses were 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<sup>nd</sup> order equation using fitted coefficients obtained by data-sheets. The required silicon area for the semiconductors was

estimated following the approach proposed by [11]. The crest factor is obtained as the ratio between the current peak and the current *rms* value. The stress across the capacitor is determined by the ratio between its current's *rms* values and the rectifier output current (cf. [9]). The rated power of inductive components (inductors and transformers) is evaluated as in [9], in such a way that the inductors are characterized by the rated power of an equivalent transformer. Fig. 14 shows the performance of each ESP system proposed in Section III regarding: system efficiency ( $\eta$ ); line current THD (up to the 25<sup>th</sup> harmonics); required silicon area ( $A_S$ ); capacitor link current stress ( $I_C$ ); magnetic rated power ( $S_L$ ); and current crest factor.

As can be noted in Fig. 13 and 14, the ESP arranged as a multi-pulse system is a very interesting solution, as the reliability of the overall system is preserved, whilst a good line power quality can be obtained. The possibility of using distribution transformers to build multi-pulse systems enhances the advantages of such a concept. In addition, the combined multi-pulse and active filter technology is very attractive for ESP applications as a compromise between reliability, high power quality and efficiency can be achieved.

The ESP power supplies employing 100% of active rectifier provides the lowest cost regarding the magnetic elements, however a high silicon area is required in this system, which implies high costs. Due to the front-end output voltage control characteristic, a max utilization of the back-end converter can be achieved. This further improves the system efficiency and also allows cost reduction for the back-end converter. Due to the recent growing development in semiconductor technology for high power applications, the ESP power supply based on Vienna rectifiers constitutes a very attractive solution for a future ESP application.

#### V. CONCLUSIONS

In this article, the energization characteristics of ESP systems are presented. The interaction between the mains and a group of power supplies feeding an ESP system was investigated. A strategy to solve the inherit problems caused by pulsed operation was shown, where the main idea is to arrange the systems pulses in an optimal sequence, so that the group of pulsed power supplies has similar line behaviour to that which an equivalent single power supply, which operates in continuous mode, would have. In addition, a simple way to improve the line power quality in ESP application by using both the characteristics of its electrical installation and the modern ESP zone high power supply was presented.

For replacement of the three-phase diode bridge rectifiers used in modern ESP power supplies (cf. Fig 2), the characteristics of multi-pulse and PWM rectifier topologies described in the literature and other concepts including hybrid systems, as well as active filters, which are suitable topology for ESP applications, is investigated. Each one of the proposed concept is discussed and evaluated for a typical ESP installation comprising 16 power supplies operating in pulsed mode. The proposed solutions are compared considering the power semiconductor losses, circuit elements stresses, etc.

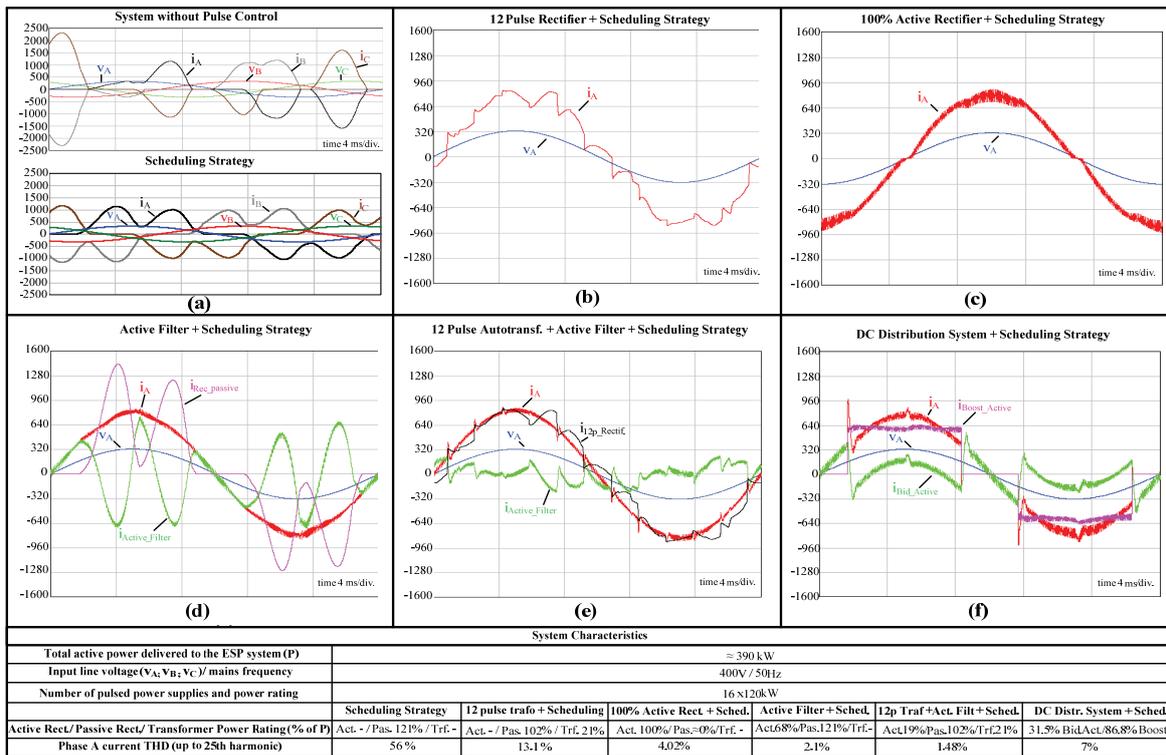


Fig. 13. Simulation results of the alternative of electrostatic precipitator systems: (a) System with and without pulse control based on the scheduling strategy proposed in [7]; (b) 12 pulse rectifier system + scheduling strategy; (c) 100% active rectifier+ scheduling strategy; (d) Active filter system + scheduling strategy; (e) 12 pulse rectifier system + active filter + scheduling strategy; and (f) DC distribution system+ scheduling strategy.

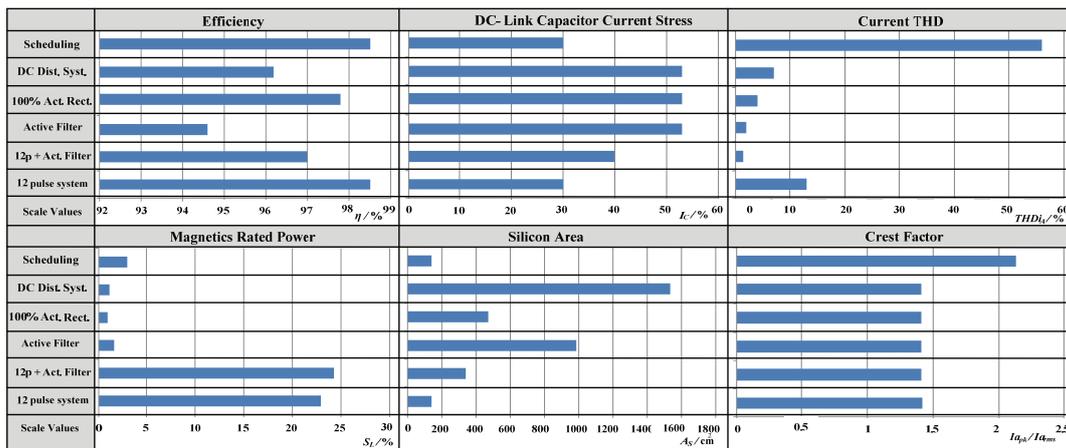


Fig. 14. ESP system evaluation charts.

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