Line Power Quality Improvement for Pulsed 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 quality are proposed. In order to reduce the Total Harmonic Distortions (THD) of the line current and also improve the loading balance between the phases, the pulses of the individual power supplies are scheduled and controlled together, so that the power consumption becomes more continuous. The proposed system optimization is experimentally verified with two commercially available ESP supplies, each having power capabilities of 120kW. The study shows the advantages of the pulses scheduling strategy namely reduction of both reactive power consumption and line current peaks; better current THD; better power balance among mains phases; and better utilization of mains components.**

Index Terms—**Electrostatic precipitator, optimization strategy, pulsed power supplies.**

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]. Modern ESPs are divided into several sections or zones 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-120kW and an output voltage range of $30kV_{DC}$ - $100kV_{DC}$ [3]. These supplies can have different converter topologies or configurations, depending on their location in the ESP [4]. In outlet zones, for example, pulsed voltages are used more and more frequently as they increase the particle collection efficiency.

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 [5], [6]. Fig. 1 shows a possible circuit diagram of an ESP power supply (cf. [3] and [6-10]). Pulsed operation influences the mains power quality considerably as it can result in high line current distortion and unbalanced mains phase loading. These problems can become worse if, for example, a group of power supplies with pulsed operation are fed by the same mains (cf. Fig. 2) as the pulses in different supplies can occur at the same instant (*critical case*). On the other hand, if the pulses in each power supply are scheduled in an optimal way it is possible to reduce the undesirable effects in this type of operation, so that the power consumption becomes more continuous in time (*optimized case*).

The interaction between the mains and a group of power supplies feeding an ESP system is investigated in the Section II of this paper. Section III proposes two methods to solve the inherit problems caused by pulsed operation. The first method uses a 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. The second method 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. Both optimization strategies can be applied to any group of power supplies operating in pulsed mode without impairing the ESP collection efficiency, whilst preserving the system reliability. Thereby, a considerable improvement of the line current by just controlling the starting time of the different pulses can be achieved without any additional means. In Section IV, the study is experimentally verified using two commercially available ESP power supplies with power capabilities of 120kW each.

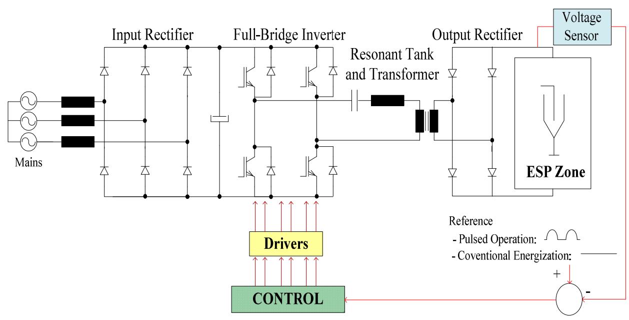

Fig. 1. Schematic of a modern ESP power supply.

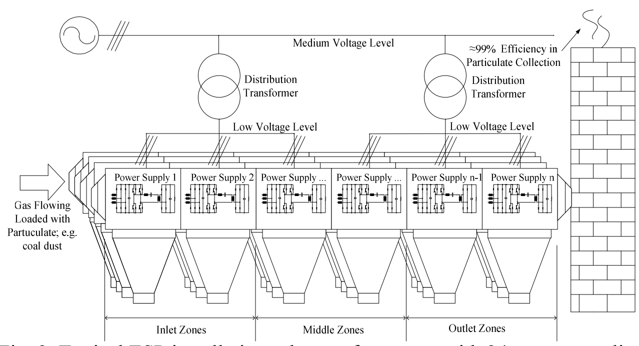

Fig. 2. Typical ESP installation scheme of a system with 24 power supplies

II. ESP Power Supplies and the Line Power Quality

In this section, the energization characteristics of ESP systems are presented. The interaction between the mains and a group of power supplies feeding an ESP system is investigated. In addition, a suitable model that describes the line current behavior of each ESP power supply for pulsed operation is presented.

A. Characteristics of an ESP system

Usually an ESP is divided into several sections or zones to improve the particle collection efficiency [2]. In small systems only two or three fields/zones are connected in series and in large ones, several zones are connected in parallel and in series [2]. Different power supplies with different power ratings often energize the sections in order to optimize the collection efficiency of the single zones (cf. Fig. 2). These zones have different electrical behavior and efficiency, due to the different dust loads of the zones, particle size and properties, and the possibility of charging particles in the entire zone using appropriate technology *e.g.* pulsed energization or continuous operation (conventional energization) [4].

Large particles and high dust loads can be addressed effectively using high frequency DC power supplies (characteristic of the inlet ESP zones) [4]. Pulsed power supplies, however, can separate fine particles more efficiently (characteristic of the outlet zones) [4].

Typically, an ESP with conventional energization operates with constant voltages in the range of 30 kV_{DC} to 100 kV_{DC}[3]. This strategy is usually applied where the particle concentration is very high; using a DC voltage level very close to the flashover limits [4]. A suitable topology for the conventional energization strategy is shown in Fig. 1 [3]. This topology can be controlled in a closed loop by feeding back the output current or voltage. However, utilizing the output current is advantageous because the output current is the variable that determines the ESP's collection efficiency.

In pulsed operation, the ESP is fed with periodic high-voltage pulses in the range of 0 to 100kV as illustrated in Fig. 4(a). This method is effective for reducing back corona, improves the collection efficiency of high resistivity dusts and 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. 1 is also suitable for pulsed mode operation by adapting the control loop reference.

B. Pulsed Operation Effects on the Line Power Quality

To illustrate the effects of the pulsed energization on the power quality of the mains, a system of five power supplies fed by the same mains was simulated (cf. Fig. 3). The power supplies of the ESP considered in this example are similar to the ones depicted in Fig. 1. Here, the following operation conditions are investigated:

a) The *"Critical Case"*: The power supplies operate in pulsed mode with pulse width of 3ms and period of 12ms. The pulses of all power supplies are arranged to occur at the same time, aggravating the problems with mains quality. Fig. 4 shows the simulation results;
b) The *"Optimized Case"*: The power supplies operate in pulsed mode, with the same configuration as the *"Critical Case"*. In this analysis, the pulses are equally distributed in a pulse period (T_P) in order to obtain more continuous power consumption (optimization by scheduling of pulse). Fig. 5 presents the simulation results;
c) The *"Best Case"*: The power supplies operate in continuous mode. This system was configured to require a similar amount of power as the *"Optimized Case"*. Fig. 6 shows the obtained simulation results. Note that the mains behavior observed in this analysis is the target of the optimization by scheduling.

By analyzing Fig. 4, one can observe that the line currents are unbalanced and highly distorted. The power balance on the mains is critical as high line current peaks 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 V_{Link}. When the capacitor voltage drops, the diode current conduction angle is increased. On the other hand, when this voltage raises the diode current conduction is blocked.

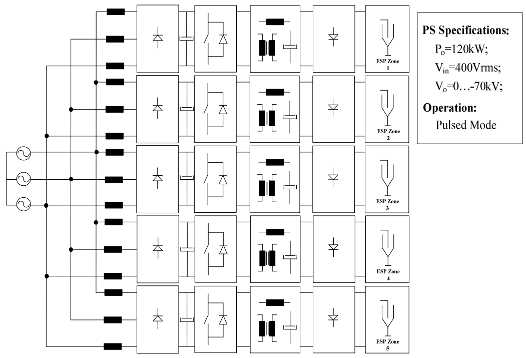

Fig. 3. System of 5 power supplies feeding an ESP system.

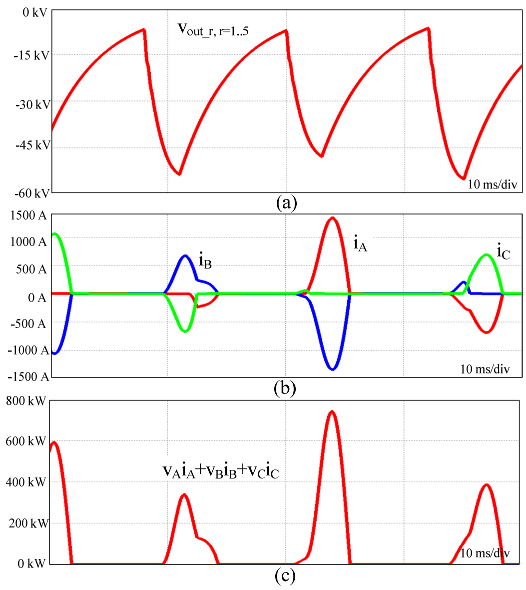

Fig. 4. Simulation results when the pulses of all power supplies are arranged to occur at the same time: (a) ESP applied voltage for each power supply; (b) Line currents; and (c) Mains' instant power drained.

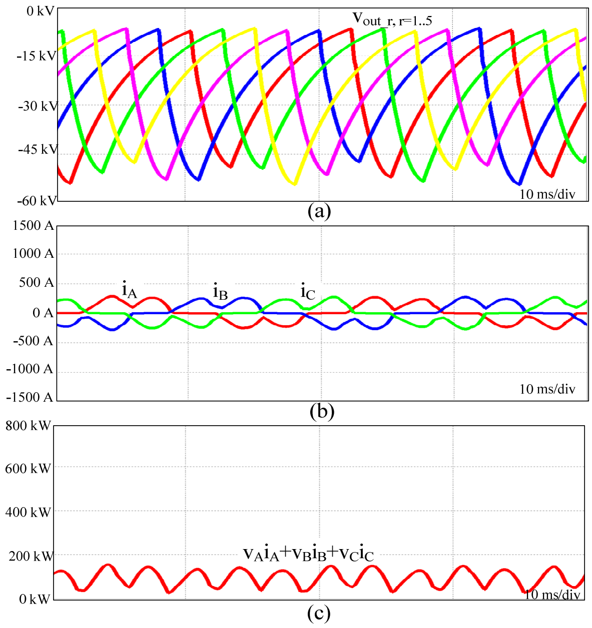

Fig. 5. Simulation results when the pulses of all power supplies are equally distributed in a pulse period: (a) ESP voltage applied for each power supply; (b) Line currents; and (c) Mains' instant power drained.

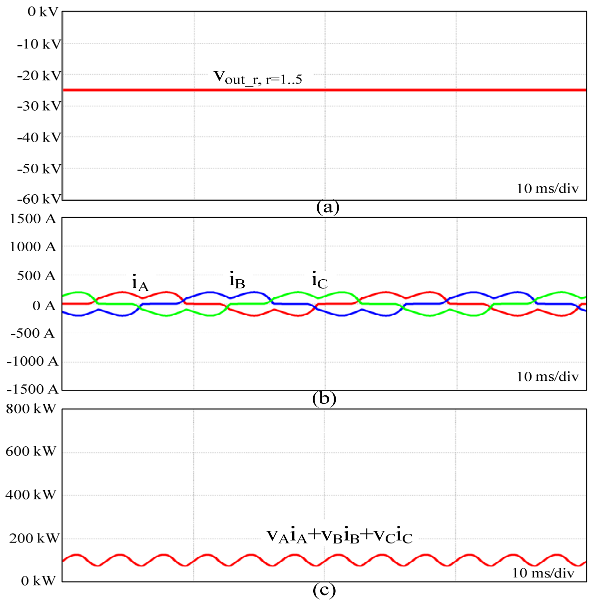

Fig. 6. Simulation results for conventional energization: (a) ESP voltage applied for each power supply; (b) Line currents; and (c) Mains' instant power drained.

As can be observed in Fig. 5 and 6, the system has a similar behavior 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"*. Moreover, one can observe that the harmonic distortion of the line current generates less oscillation on the electric power demanded (cf. Fig.5 (c)). In terms of power quality, the ideal scenario is considered to be when the line current absorbed by the power supply and voltages of the mains are in phase, with sinusoidal waveforms. In this case, the ESP system would operate with a unity power factor, draining constant power from the mains over time. Note that in this analysis the voltages of the mains are purely sinusoidal and for this reason the oscillations observed on the instant power waveform are due to the line current harmonics.

C. Line Current Prediction for Pulsed ESP Systems

The minimization of line current distortions and load unbalance between the phases caused by the pulsed operation in a group of power supplies can benefit from the use of optimization strategies. This is particularly true once the pulses of the individual power supplies can be scheduled in an optimal way so that the system power consumption becomes more continuous (cf. Fig.5). Therefore, the goal of the optimization is to find a set of system pulse parameters which improves the line currents/power consumption while not impairing collection efficiency of the ESP system.

The first step to solve the optimization problem is to find a suitable model that describes the line current behavior of each ESP power supply for pulsed operation. In the system considered the power supplies have the circuit diagram as shown in Fig. 1. For this topology with a high frequency filter placed at the input of the full-bridge inverter, a typical current waveform drained by the resonant converter in pulsed operation is shown in Fig. 7(a). As one can observe, the back-end converter behaves as a current source *i(t)*. It demands current when the power supply is pulsing and no current when this pulse stops (cf. Fig. 7(a)). This operation condition is derived from the pulsed mode control, which switches the IGBTs at high frequency, when the pulse is on and turns them off otherwise.

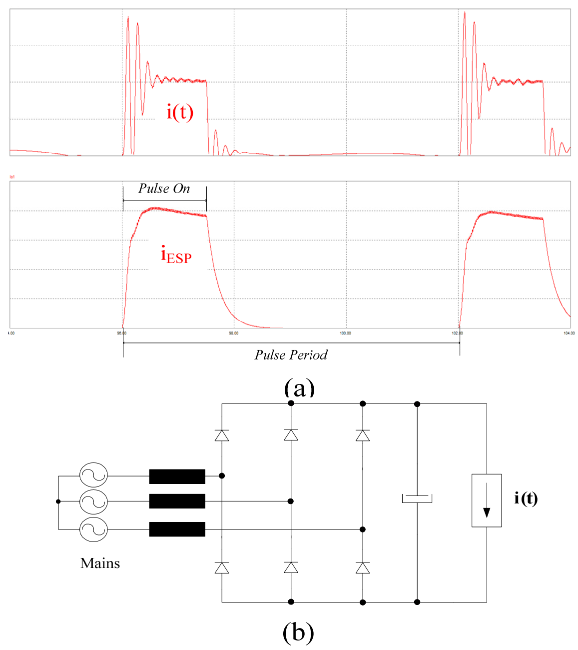

Fig. 7. ESP power supply model: (a) typical current drained by the resonant converter *i(t)* and ESP drained current i_{ESP}; and (b) ESP power supply circuit model.

The line currents' time response of the ESP system can be calculated by first identifying in which state the converter model is and then by calculating the run of the currents with the corresponding model. As presented in Fig. 8, eight states or equivalent circuits can be identified in one pulse period. As shown in Fig. 9 and 10, these states are iteratively determined according to the pulse time instants (start and end), line-to-line voltage, DC link voltage and the running line currents.

In order to verify the accuracy of the proposed model a commercial ESP power supply, operating in pulsed mode with $PW=1.5ms$ and $T_p=5ms$, was tested and the result compared to the one predicted by the model as shown in Fig. 11. In this analysis, a very good correspondence could be observed validating the analytical considerations.

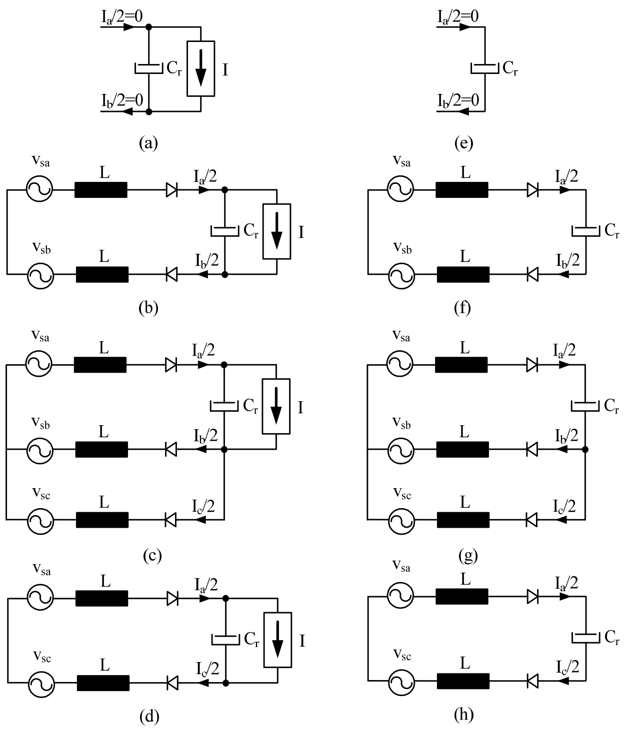

Fig. 8. Possible converter model's operation states (a) to (h).

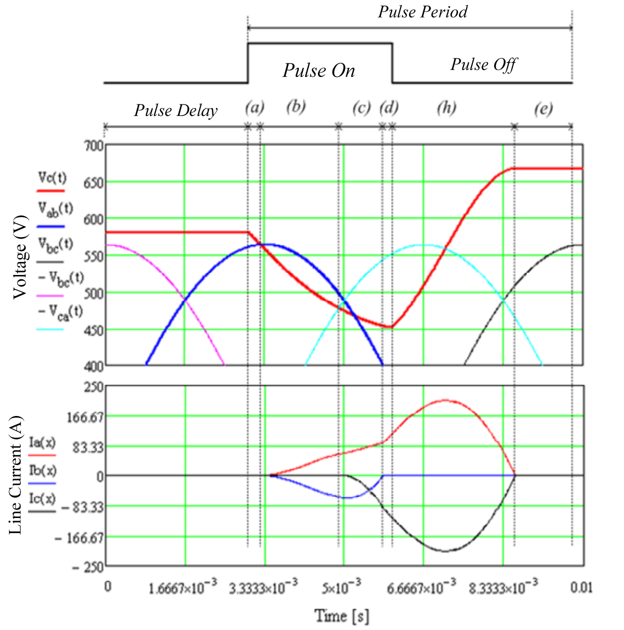

Fig. 9. Typical ESP's power supply line current waveforms. Note that the running operation states are shown.

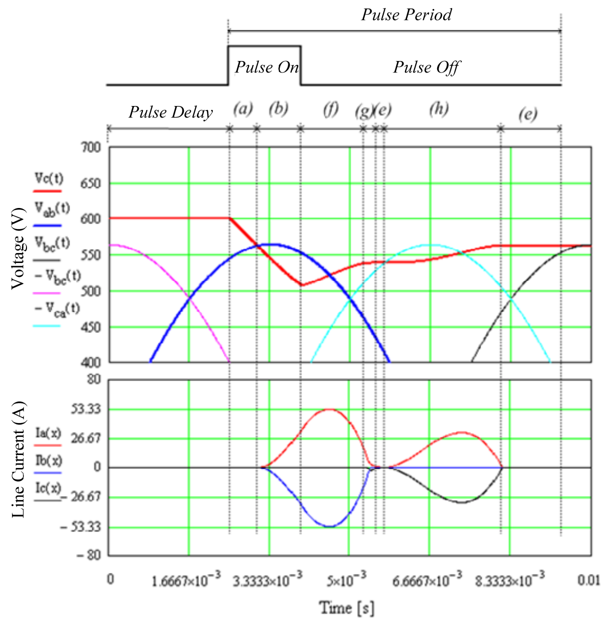

Fig. 10. Typical ESP's power supply line current waveforms. Note that the running operation states are shown.

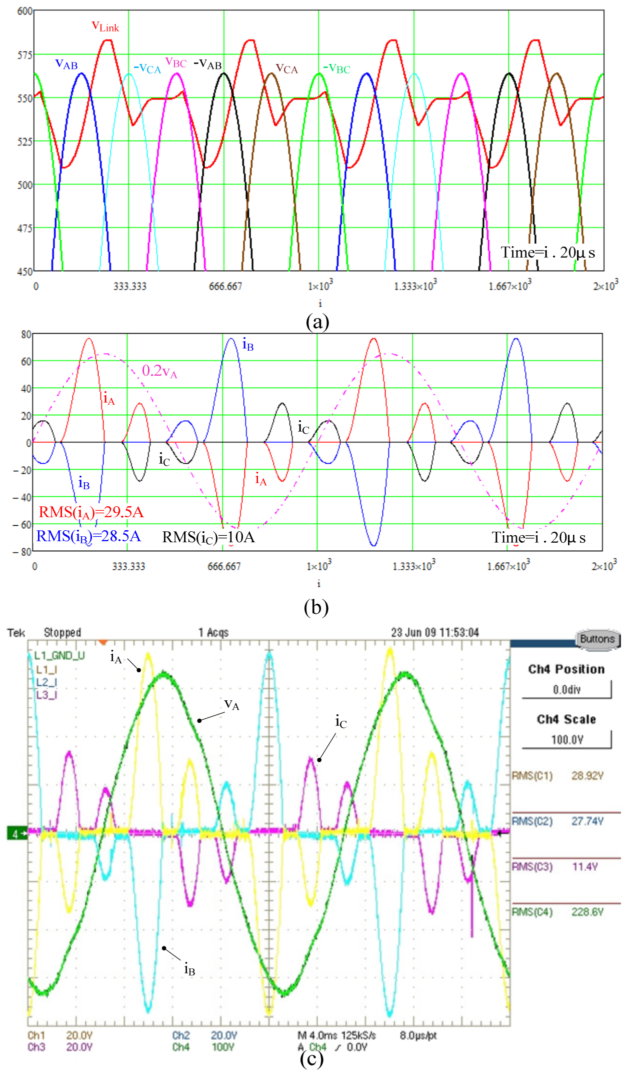

Fig. 11. (a) DC link voltage prediction, (b) Line current predicted by the proposed model; and (c) Experimental set-up waveforms (cf. schematic depicted in Fig. 1 and test set-up in Fig. 16).

III. Optimization of ESP Pulsed Operation Mode

This section proposes two methods to solve the inherit problems caused by pulsed operation. The first method uses the time domain sampled-data model proposed in II c) 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. The second method presents an algorithm which schedules pulses to fill the gaps between a pulse reference and the pulses of the other power units in order that the system's power consumption becomes more continuous.

A. *Optimal Strategy (OS)*

The OS optimization idea is presented in the flowchart in Fig. 12. The time response of the system line currents are predicted by adding up the currents of each ESP system's power supply, which result from a given set of pulse parameters. This evaluation is based on the developed model of the converter input currents for which the input consists of the following pulse parameters (cf. Fig. 13): Pulse Width (PW), pulse period (T_p), pulse delay (φ) and current drained by the back-end converter (I_m).

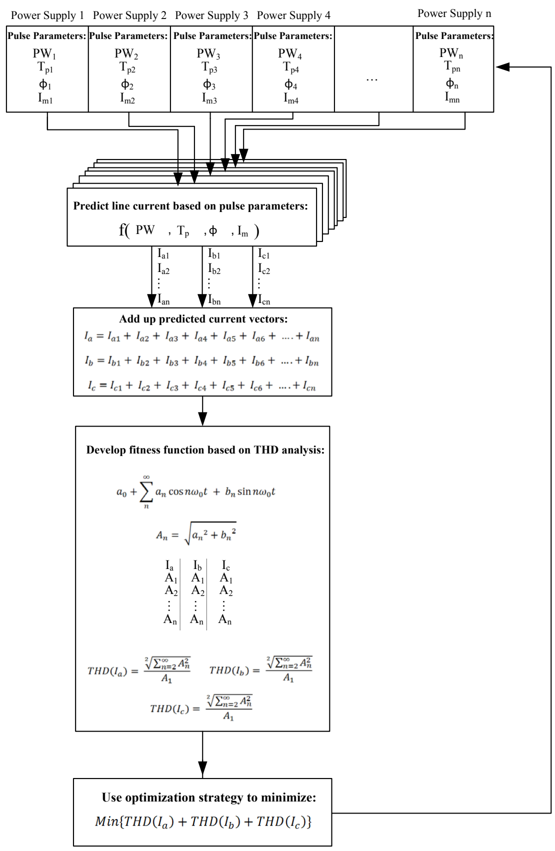

Fig. 12. Optimal strategy flowchart.

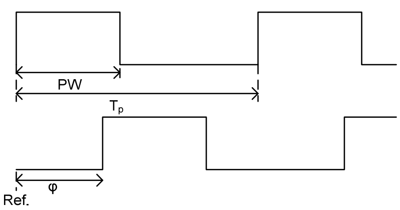

Fig. 13. Pulse parameters.

The current harmonics are calculated with the predicted waveforms of the line currents. In the next step the fitness function $f(I_a,I_b,I_c) = THD(I_a) + THD(I_b) + THD(I_c)$ is built and an optimization algorithm is applied to minimize it in an iterative process. Other criteria could be used as optimization functions, e.g. minimal sum of line current RMS values (or minimal RMS difference), minimal line current peaks, etc.

Due to the fact the model/equations are different for each state, the use of local optimization strategies e.g. Conjugate Gradient methods, Quasi-Newton Methods, etc.; become very difficult as these are unsuitable for problems with non-differentiable and/or discontinuous regions [11]. On the other hand, global optimization methods like Random Walk, Simulated Annealing and Genetic-Algorithms (GA) [12], etc; are more robust when faced with discontinuous solution spaces and/or high dimensional systems with many potential local optima [11]. In this work, the MATLAB optimization toolbox is used as an optimizer.

The complexity of the optimization problem can be seen in Fig. 14. The fitness function is plotted as a function of the pulse time delay for two power supplies with pulse parameters: PW: 1.5 ms, T_P: 6 ms and varying pulse delay φ: [0, 20 ms]. As can be seen, the THD of the line currents strongly depends on the pulse delay and many local minima in the existing searching space solution occur. Note that high THD values are normally found when the power supplies' pulses are released at the same instant in time and that the best THD results are for equally distributed pulses in the pulse period range. Based on this, a simple optimization strategy is derived, as presented in Section III-B.

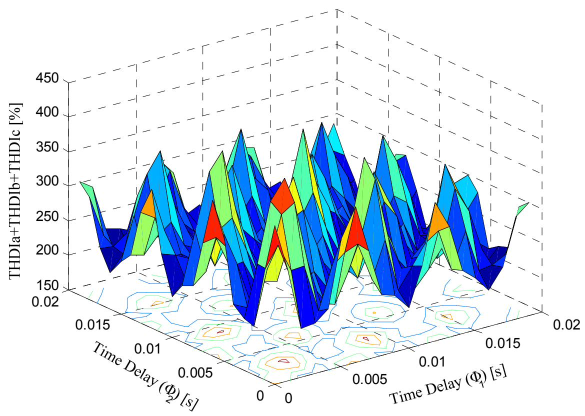

Fig. 14. Dependency of the line currents' THD on the time delay in a group of two power supplies.

B. *Empirical Strategy (ES)*

The schedule of pulses is optimized by shifting the initial pulses of each power supply by a delay time with respect to one pulse reference. The power supply with the largest pulse period (Tp_r) is taken as a reference for the others. The aim is to fill the gaps between the reference pulses with the pulses of the other power units, so that the system power consumption becomes as continuous as possible. This process continues until all the power supplies are analyzed. The flowchart describing this optimization procedure is shown in Fig. 15. The variables of the pulse delay δ_{Pri} and gaps are given by the expressions (1) and (2) respectively, where n_{PS} is the number of power supplies being optimized and PW_{PSi} is the pulse width of the power supply *i*. The letter *r* stands for the number of the reference power supply.

$$\delta_{Pri} = k\frac{Tp_r - \sum_{z=1}^{n_{PS}} PW_{PSz}}{n_{PS}} + PW_{PSr} + \sum_{z\neq r=0}^{i-1} PW_{PSz} \qquad (1)$$

$$gap_{Fj} = \frac{Tp_r - \sum_{z=1}^{n_{PS}} PW_{PSz}}{n_{PS}} \qquad (2)$$

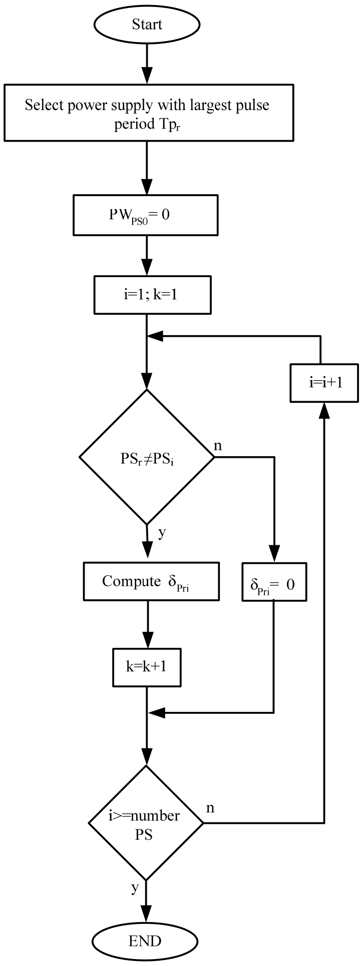

Fig. 15. Flowchart describing the empirical strategy optimization procedure. This algorithm is used to equally distribute the pulses of each power supplies in the largest pulse period of the analyzed system.

C. Optimal Strategy vs. Empirical Strategy

In order to evaluate the system's gain in power quality, the proposed optimization methods were applied to an ESP system similar to the one used in Item II-B. In this analysis the pulses of up to eight power supplies were optimally scheduled. Fig. 16 shows the results obtained for both methods, OS and ES, where the sum of the THD values of the line currents is illustrated together with the line current waveforms predicted by the system model.

In Fig. 16 it can be noted that the more power supplies a system comprises, the lower the influence of the parameters of one system on the overall THD. However, the line power balance continues to improve (behavior more similar to continuous operation).

The OS strategy always obtains better results than the ES one, but the computational time cost is much higher. The ES strategy is easy to implement and can be used in real time pulse scheduling, *e.g.* to re-schedule the system in case of malfunctioning PSs, flashovers, etc. In comparison with the ES results the reduction of total current THD with OS is as high as the number of power supplies in the system is small. Usually for more than 4 power supplies the gain in THD reduction is less than 5% ($THD(I_a)+THD(I_b)+THD(I_c)$) making the use of the OS strategy unjustifiable when the ESP system has more than 5 PSs (which is normally the case).

In case of flashovers (short-circuits of the power supply output), the pulse parameters, which would be resulting for ideal operation in both proposed strategies, may no longer lead the system to an optimized performance. In order to overcome this problem and also to avoid real-time pulse scheduling, the following actions can be performed in order to fill the created pulse gaps:

- Some power supplies, which are pulsing in the instant when the flashover is detected, can have their pulse width extended;
- Some power supplies, which are not pulsing in the instant when the flashover is detected, can be set to start pulsing earlier than the normal set instant.

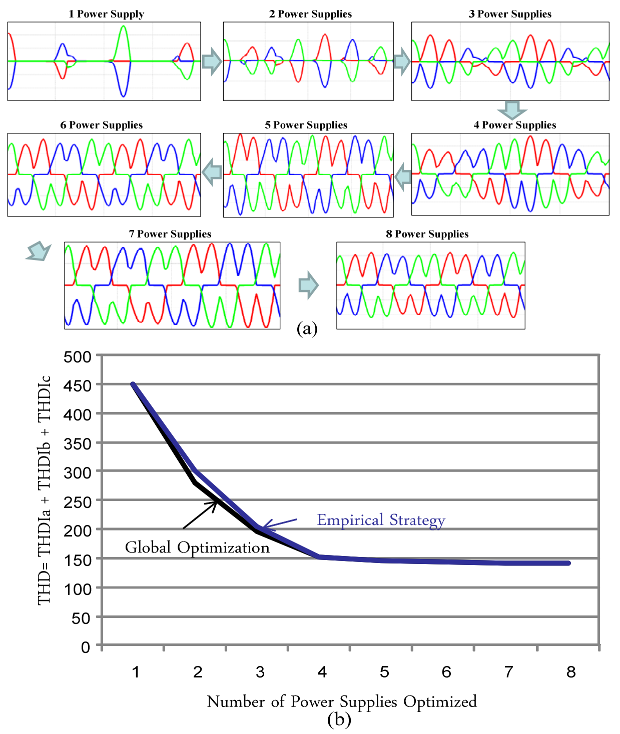

Fig. 16. Scheduling of pulses applied to different number of power supplies: (a) current waveforms analysis for OS; and (b) Current THD results for OS and ES strategies.

IV. Experimental Results

The improvement in line power quality achieved with the scheduling strategy is verified experimentally by a 240kVA system comprising two commercially available ESP power supplies fed by the same mains (cf. Fig. 17).

The main circuit waveforms for the analysed ESP power supplies operating in pulsed mode can be seen in

Fig. 18. Therein, the resonant tank current of the back-end converter (i_{Ls}), the output voltage V_{ESP}, the output current i_{ESP}, and the bus-bar capacitor voltage V_{link} are shown. Fig. 19 shows, at the instant the pulse is released, the resonant current i_{Ls}, the IGBTs full-bridge output voltage V_{AB}, and the transformer primary voltage V_{pri} behaviours. Note that before the pulse is released no current is drained by the back end converter ($i_{Ls}=0$), and when the pulse is on, a high frequency current is demanded. As can also be observed, the bus-bar capacitor voltage varies considerably, causing high distortions in the line currents.

The two power supply system is set to operate in pulsed mode with a pulse configuration of 5ms pulse width and 10ms pulse period. Fig. 20 presents the results for the case where each power supply pulse is arranged to occur at the same time (critical case). The optimized system behavior is shown in Fig. 21, where a pulse delay of 5ms is set between the two power supplies. Note that in this ESP system both optimization strategies (OS and ES) give an output with a very similar pulse delay. The characteristics of both experiments are summarized in Table I. Analyzing the data from Table I, one can list the advantages of the pulse scheduling strategy as: reduction of power consumption; reduction of line current peak value; better current THD; better power balance among mains phase; and better utilization of mains components.

In Fig. 11, 21 and 22 the accuracy of the ESP experimented system model is verified, where the experimental results are compared to the ones predicted by the proposed model. A very good correspondence can be observed which validate the analytical considerations of the proposed ESP pulsed power supply model. The continuous operation is also analyzed and the results can be seen in Fig. 22.

TABLE I- SYSTEM'S LINE CURRENT CHARACTERISTICS SUMMARY

Characteristic	Critical case	OS/ES case
Total apparent power	88kVA	75kVA
Current THD (Ch1, Ch2, Ch3)	43.2% ; 88% and 82.24%	43.7% ; 44.3% and 45.8%
Max. Peak Current	320 A	220 A
Max. mains phases power unbalance	16 kVA	4.4 kVA

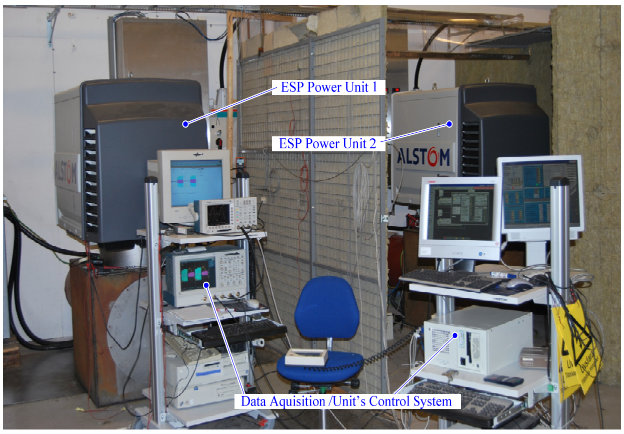

Fig. 17. Test set-up comprising two commercially available ESP power supplies fed by the same mains.

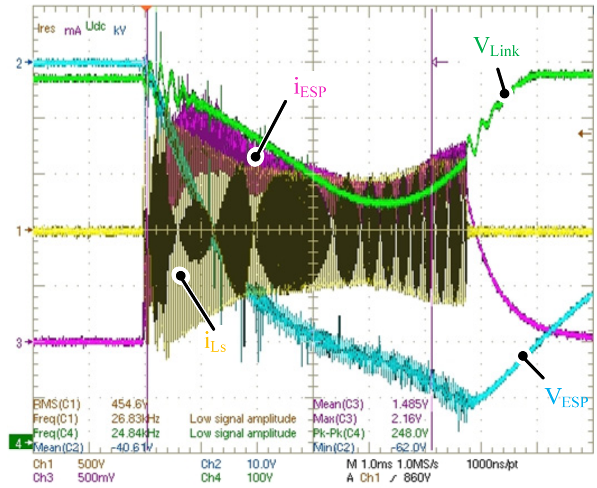

Fig. 18. Pulsed operation main waveforms: resonant tank current i_{Ls}; output voltage V_{ESP} (1V=1kV) and current i_{ESP}; and the bus-bar voltage V_{link}.

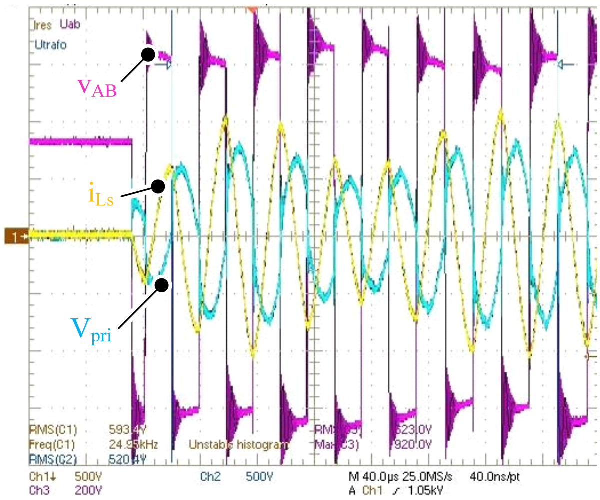

Fig. 19. Pulsed operation main waveforms: resonant tank current i_{Ls}; full-bridge output voltage V_{AB}; and transformer primary voltage V_{pri}.

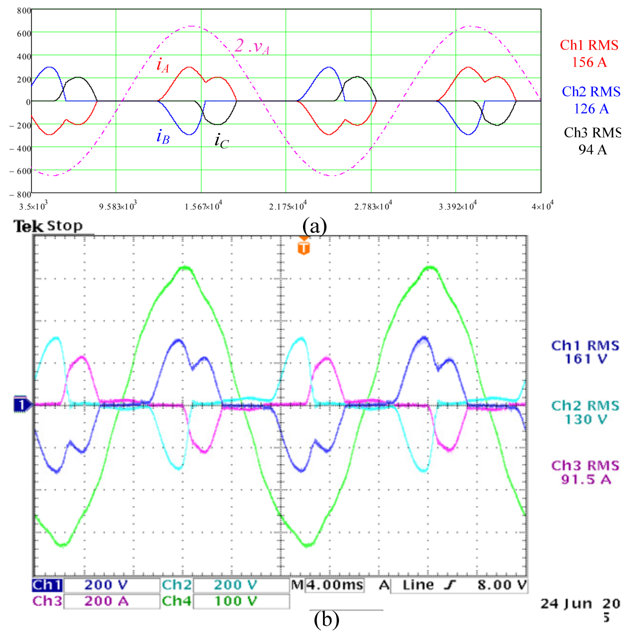

Fig. 20. Critical case: (a) Line current model prediction; and (b) Experimental set-up waveforms.

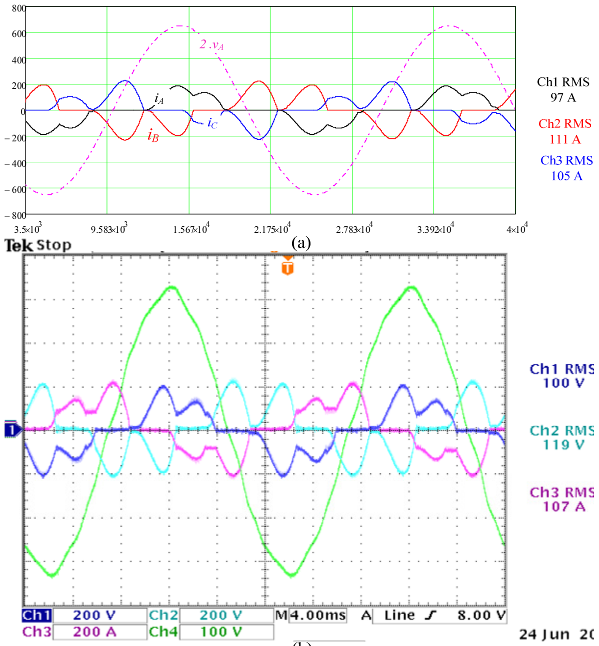

Fig. 21. Optimized case: (a) Line current model prediction ; and (b) Experimental set-up waveforms.

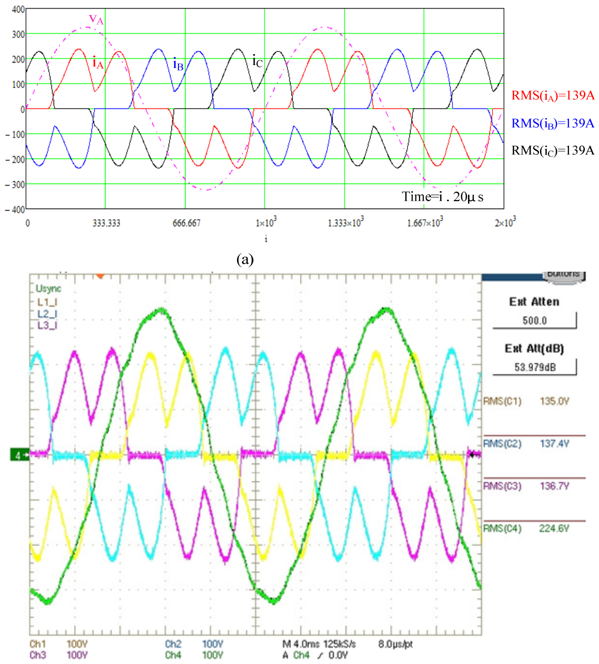

Fig. 22. Continuous operation: (a) Line current model prediction; and (b) Experimental set-up waveforms.

V. CONCLUSIONS

In this article, the line current optimization of a group of power supplies feeding an ESP system in pulsed mode was presented. The effects of ESP power supplies on the mains power quality were investigated for pulsed operation. Without line current optimization, unbalanced mains phase loading, high line current peaks and high harmonic distortions were observed. In order to improve the line power quality two optimization strategies which schedule the individual pulses of each power supply were presented. The optimized system has similar behavior to an equivalent power supply operating in continuous mode. The benefits of this optimization strategy were experimentally verified with two commercial ESP power supplies and can be listed as: reduction of apparent power consumption (-15%); reduction of line current peak value (-31%); better current THD (-37% for $THDI_a+THDI_b+THDI_c$); better power balance among mains phase; and better utilization of mains components.

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