Line Power Quality Improvement for ESP Systems Using Multi-pulse and Active Filter Concepts

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Abstract- **A simple way to improve the line power quality in Electrostatic Precipitator (ESP) applications by using both the characteristics of its electrical installation and the typical ESP high power supply is presented in this work. A multi-pulse system is built by selecting a combination of suitable MV/LV distribution transformers, preserving the simplicity and reliability of the typical ESP installation. In addition, processing only about 10% of the total system apparent power, shunts Active Filters (AFs) are placed on the low voltage side of the transformer (LV) for high order harmonic-current-mitigation (>7th harmonic). In case of imbalance in the transformer loading, the AFs can also act to adjust the current 5th and 7th harmonics, which are then effectively eliminated by the multi-pulse system. The theory presented in this work is verified experimentally by a 12 pulse system comprising two passive rectifiers and a designed 12kVAr active filter.**

I. INTRODUCTION

Due to increasing concern about environmental pollution, the reduction of particle emissions of coal fired power plants through the use of Electrostatic Precipitator (ESP) filters is of paramount importantance [1].

Industrial ESPs are normally divided into several sections or zones in order to increase the dust particle collection efficiency [2]. Each of these sections has its own power supply, which is controlled individually and has a typical output power range of 10kW to 120kW and output voltage range of $30kV_{DC}$ to $100kV_{DC}$ [3]. In this system, the power supplies can have different topologies or configurations depending on their location in the ESP. In middle and outlet fields, for example, pulsed voltages are used more and more often as they increase the collection efficiency significantly [4]. Continuous energization is normally employed in inlet field where the particulate concentration is very high [4].

Nowadays, power supplies of modern ESPs often employ a three-phase diode bridge rectifier as a front-end converter due to its simplicity, reliability and low cost (cf. Fig. 1) [5-8]. The main drawback of this concept is that diode rectifiers inject significant current harmonics into the power system. This could overload 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 significantly 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.

A typical ESP electrical installation is depicted in Fig. 2, where due to the large number of ESP zones and the high power processed, a dedicated substation with two or more distribution transformers is commonly used. Therein, 3-phase transformers providing phase shift between primary and secondary windings as a multiple of 30 degrees could be employed to feed the power supplies of the ESP. 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 is highly dependent on the load balance between the secondary sides of the transformers, which could be difficult to achieve in an ESP system, as the ESP zone loading characteristics can vary considerably.

To further improve the line quality, ensuring agreement with harmonic guide lines, shunt active filters (AFs) can be employed; however, they need to cope with the high dynamic loading of the ESP system. Moreover, the location of the active filter plays an important role in the total efficiency of the system and the cost of this converter.

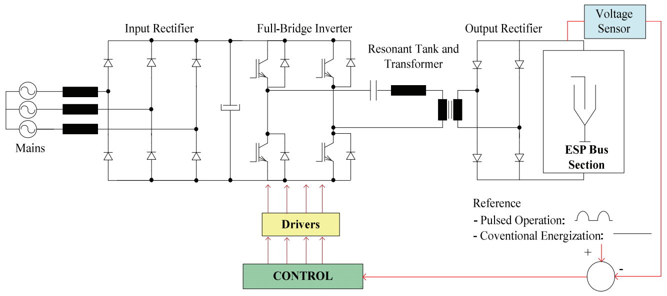

Fig. 1. Schematic of a power supply of a modern ESP.

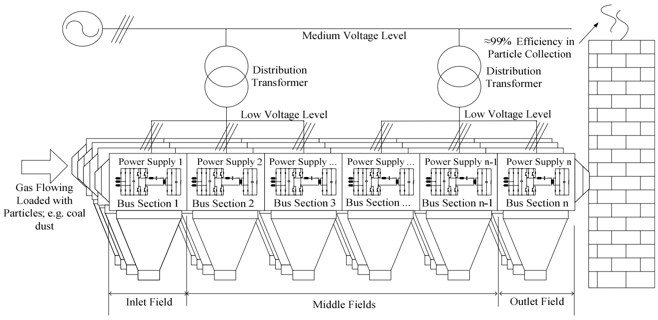

Fig. 2. Typical ESP installation scheme of a system with 24 power supplies.

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In order to avoid measurements on the MV side for controlling the active filter, a control concept based on a transformer model is proposed in this paper. This predicts and adjusts the line currents on the MV side for the AF's current reference generation, only by sensing the currents of the ESP power supplies on the transformers' LV side. Due to the fact that only small calculations are necessary, delays to the reference signal processing are minimized, and control strategies, which are commonly used in AF solutions, can be adapted without degrading the overall performance of this converter. The AFs are intended for high order harmonic-current-mitigation (>7th harmonic), and to balance the 5th and 7th current harmonics, which can then be effectively eliminated by the multi-pulse system. The ESP system becomes highly efficient because the active structures (AFs) only process about 10% of the total system apparent power.

The line quality improvement achieved with the proposed study is verified experimentally by a system comprising two passive rectifiers. Therein, the electrical installation is arranged in such a way that each 12kW rectifier unit is fed by line voltages phase-shifted by 30 degrees in relation to each other by the use of one Delta to Wye transformer (ΔY or Dy1). Finally, a 12kVAr AF is added to mitigate the remaining harmonic of the constructed 12 pulse system.

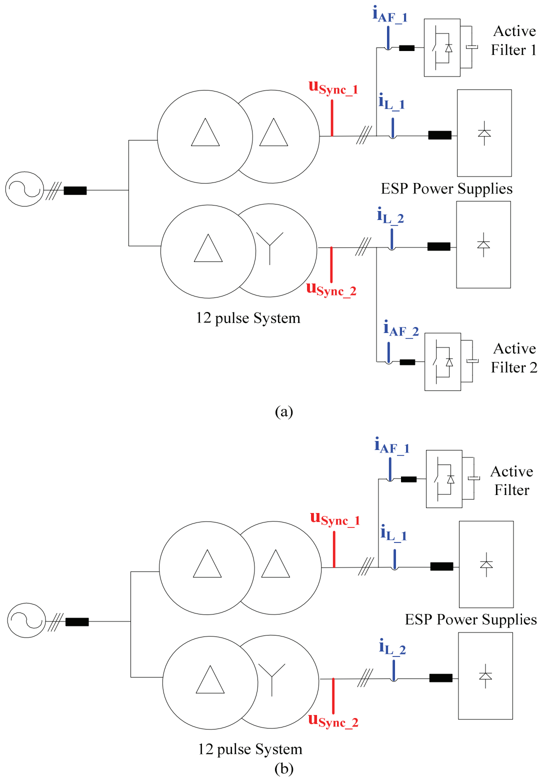
II. ESP SYSTEM USING MULTI-PULSE AND ACTIVE FILTER SYSTEMS

In order to improve the line power quality of an ESP system, this work proposes a highly efficient system configuration comprising of two parts:

- A multi-pulse system, which can be built by proper selection of distribution transformers in a typical ESP electrical installation (cf. Fig. 2). The main objective of this system is to eliminate the 5th and 7th harmonics of the line current on the transformer's MV side.
- Active filters intended for high order harmonic-current-mitigation (>7th harmonic), and to balance the 5th and 7th current harmonics, which can then be effectively eliminated by the multi-pulse system. The AFs are installed on the low voltage transformer side in order to use standard low voltage IGBTs and circuit components with better loss characteristics.

The proposed systems are depicted in Fig. 3. Both arrangements comprise of two MV/LV distribution transformers configured as a multi-pulse system (Dd0 and Dy1 in this example) feeding two ESP power supplies (cf. Fig. 1) and shunt active filters installed on the low voltage side of the transformer. As can be observed in Fig. 3 there is the possibility of using one or more active filter structures. Regarding the line current harmonic mitigation capability, the solution employing multiple active filters is more reliable as even in the case of failure of some the AFs, the system can still achieve good line current shape with the remaining working structures.

As shown in Fig. 4, there are other possible arrangements for ESP systems employing multi-pulse and active filter concepts; however they would result in additional costs when compared to the proposed arrangement. The active filter could be installed directly on the MV side (cf. Fig 4(a)); however MV semiconductors/sensors would be required. An auxiliary MV/LV transformer could be used to feed the active filter on the MV side, allowing the use of standard semiconductors and sensors (cf. Fig 4(b)). A hybrid active filter could be employed (cf. Fig 4(c)), but high voltage rating passive elements would be required. A special distribution transformer with an additional secondary winding could also be used to feed the active filter (cf. Fig 4(d)).



(a)

(b)

Fig. 3. ESP system using multi-pulse and active filter systems: (a) System using two active filters; and (b) System using one active filter.

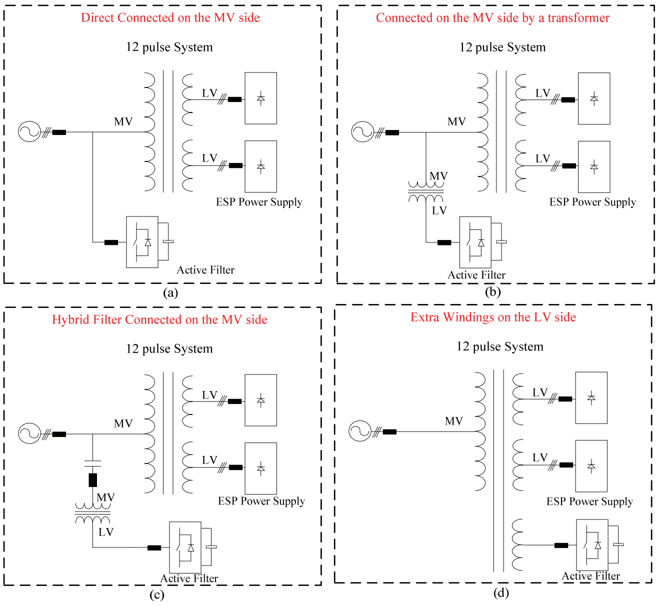


Fig. 4. Alternatives for ESP system using multi-pulse and active filter concepts: (a) AF directly connected to the MV side; (b) AF + auxiliary transformer installed on the MV side; (c) Hybrid AF connected to the MV side; and (d) System employing special distribution transformer.

A. *Multi-pulse Transformer Current Model*

In order to enable the AF operation on the low voltage side of the transformer, the AF units need to predict, or directly sense the current on the transformer's MV side. In order to avoid measurements on the MV side, an adjustment in a typical AF current reference generation strategy is proposed as shown in Fig. 5. The idea is that all the AFs equally compensate the harmonics which could not be eliminated by the multi-pulse transformer. Therefore, instead of directly using the ESP power supply currents as reference for the AF, as would be done by a traditional harmonic detection method, the proposed control strategy uses the current generated by a mathematical model of the transformer. This model predicts the line currents in the high voltage side of the transformer by sensing the current of the ESP power supplies in the low voltage side of the transformer (cf. Fig. 6). These currents carry information about the harmonics that need to be filtered (harmonics that the transformers could not fully compensate). By adjusting proportionally the predicted currents to the low voltage side of the transformer according to the transformer turns ratio and configuration, the reference of each AF will be the same, but the transformer phase-shift (30 degrees in the 12 pulse system case) is considered.

Summarizing, the main functions of the transformer model are:

1) Mathematically subtract the harmonics which the multi-pulse transformer would eliminate from the measured current; and
2) To adjust the current reference according to the transformer side, where the AF is located, with proper phase shift and magnitude.

It is important to mention that the current model of the transformer could also be adapted for other 12 pulse system configurations, such as Dy1-Dz2, Yd1-Dd0, Dz0-Dy1, etc. For other cases, the new transformer, which has the lead secondary voltage, takes the role of the Dd0 transformer and the lagged one takes the position of the Dy1 transformer in the current model.

Due to the fact that only small calculations are necessary, delays to the reference signal processing are minimized and control strategies, which are commonly used in AF solutions, can be adapted without degrading the overall performance.

Note that the shunt active filter control strategy used here was the dq-frame [9]; however other strategies such as PQ-theory, Fryze currents, generalized integrators, frequency domain strategies (DFT, RDFT and FFT), etc. (cf. [9]), could also be employed. In addition, the synchronization voltages u_{Sync_1} and u_{Sync_2} can be used to adjust asymmetries on the transformer windings coupling, by modifying the transformer turns ratio, *n*, of the proposed model for each single phase (cf, Fig. 6).

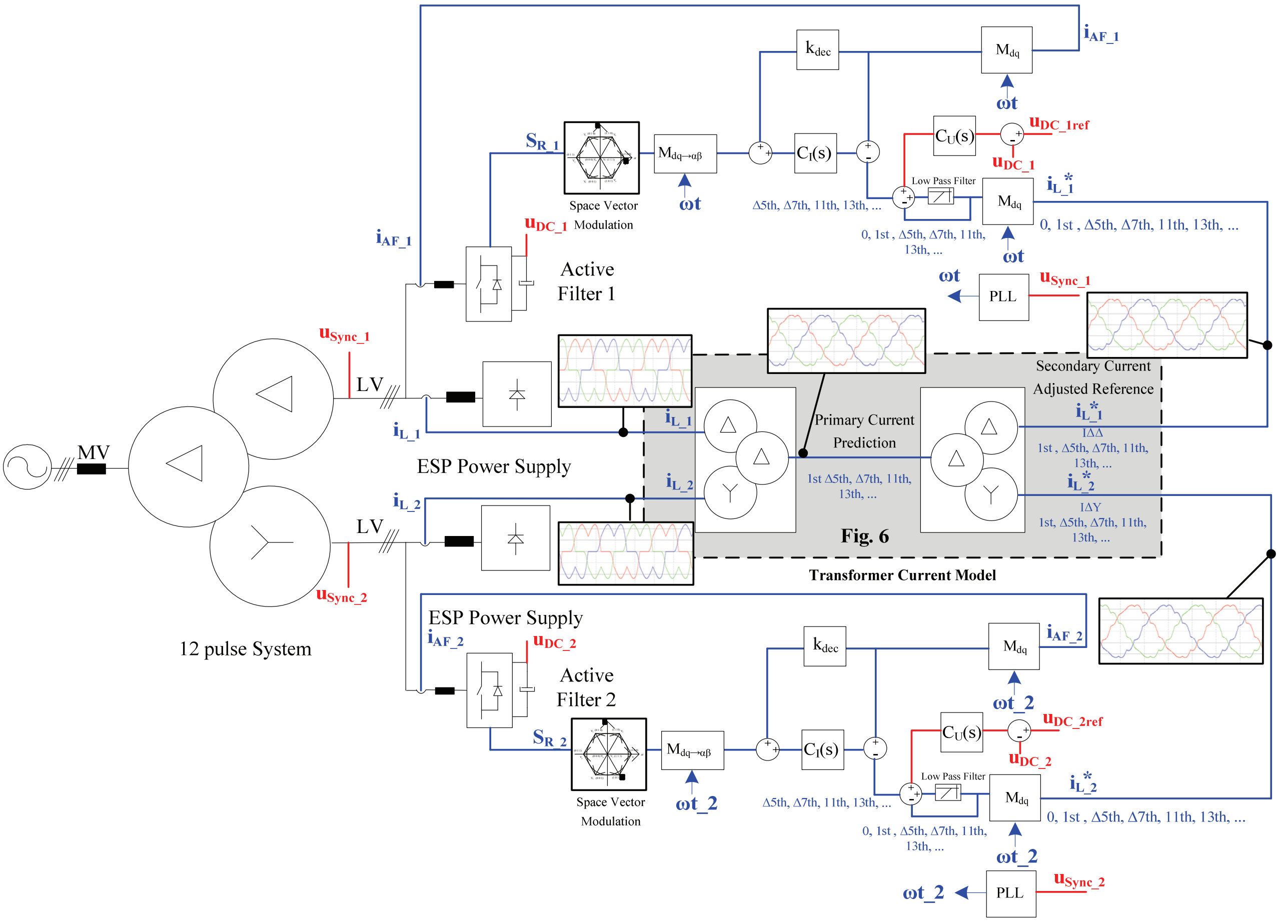


Fig. 5. ESP system proposed control strategy based on the DQ Frame theory. The control depicted here is also valid for one active filter solution; however only one current reference needs to be adjusted (either $i_{L\_1}^*$ or $i_{L\_2}^*$) as presented in Fig. 6, the other active filter and control structure can be omitted.

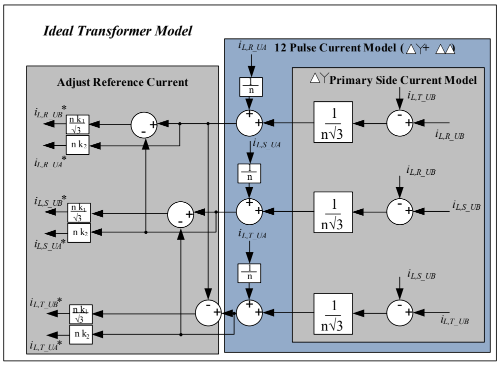


Fig. 6. Transformer model, where *n* represents the turns ratio. For the case where 2 AFs are used (cf. Fig. 3(a)), k_1= k_2= 0.5; for only one AF installed on the Dd0 transformer secondary side (cf. Fig. 3(b)), k_1=0 and k_2= 1; and for only one AF installed on the Dy1 transformer secondary side, k_1=1 and k_2=0.

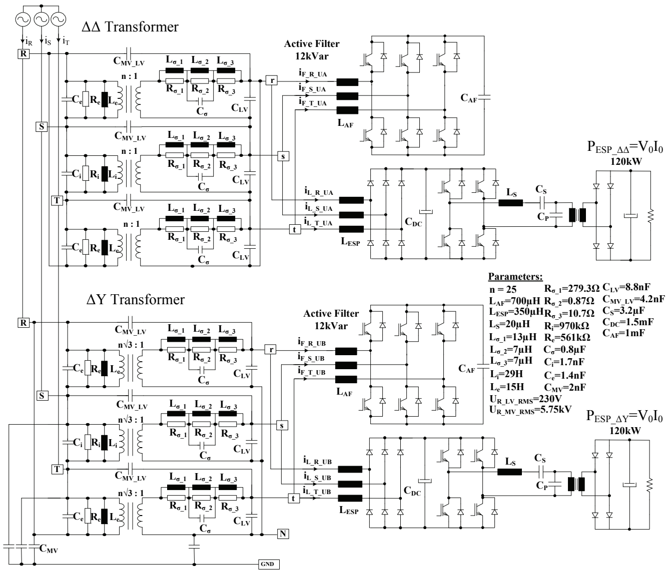


Fig. 7. ESP system comprising of a 12 pulse system and two active filters.

B. ESP System Performance Analysis

In order to verify the proposed study, the ESP system depicted in Fig. 7 was simulated. In this analysis the frequency dependant model of a MV/LV oil power transformer presented by [10] is considered for both transformers. The system performance for highly dynamic ESP loading, where two AFs are installed on the secondary side of the 12 pulse system, is shown in Fig. 8. As one can observe, the AFs effectively compensate the current harmonics, and the system draws sinusoidal current from the mains (cf. Fig. 8(a)). Note that, although the two transformers process different amounts of power (cf. Fig. 8(b) and 8(c)), the AFs process the same amount of reactive power (cf. Fig. 8(d) and 8(e)). This is due to the transformer current model (cf. Fig. 6), which makes the reference of all AFs equal.

The proposed system behavior for the case where transformer parameters are asymmetric is shown in Fig. 9. The transformer turns ratio and leakage inductances for each transformer's windings are set to be asymmetric (Dd0: nR=1.03n ($L_{\sigma R}$=100μF), nS=0.99n ($L_{\sigma S}$=350μF), nT=1.02n ($L_{\sigma T}$=50μF); Dy1: nR=1.732n ($L_{\sigma R}$=80μF), nS=1.698n ($L_{\sigma S}$=200μF), nT=1.767n ($L_{\sigma T}$=400μF)). As can be observed,

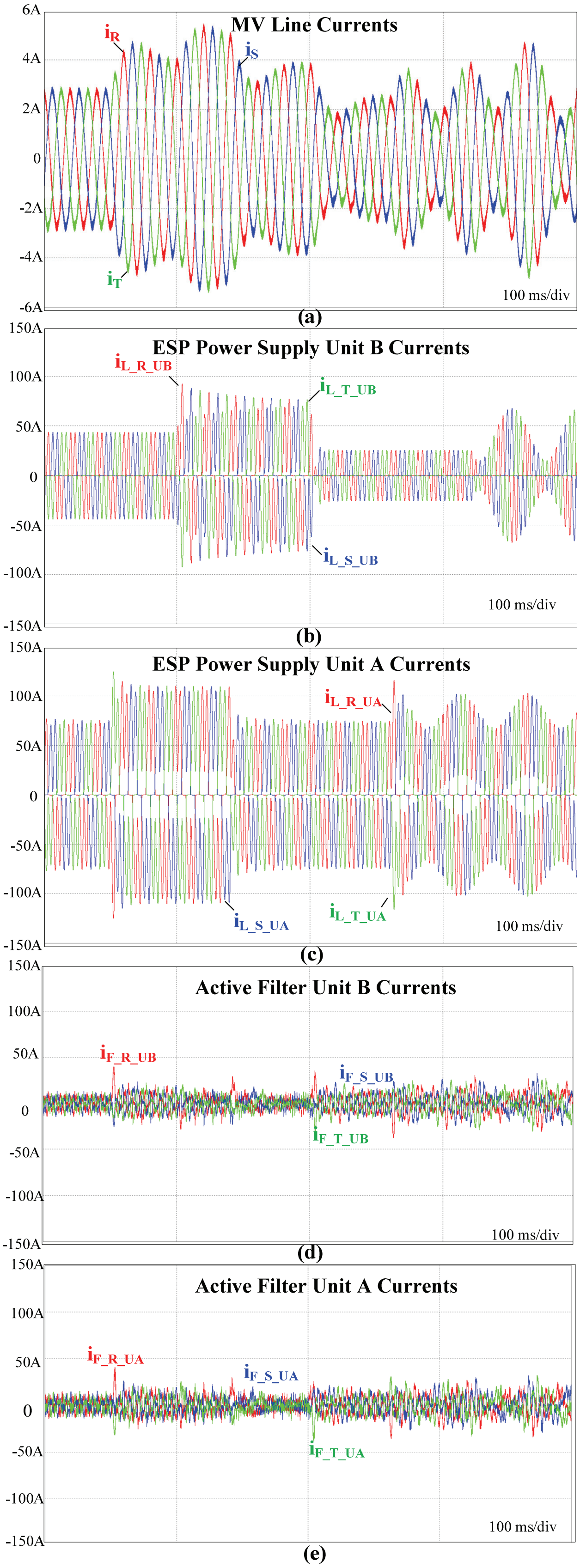
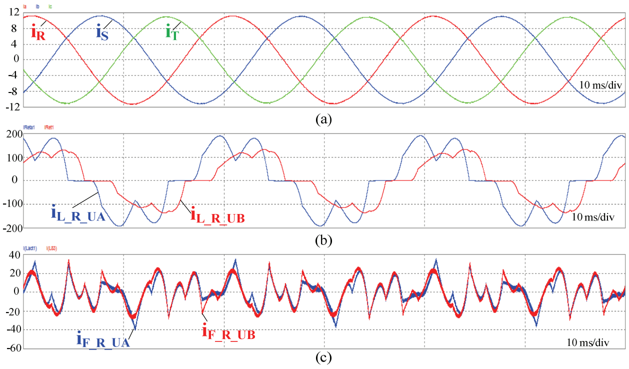


Fig. 8. Highly dynamic loading analysis: (a) System's line current; (b) ESP power supply B's line currents; (c) ESP Power supply A's line currents; (d) Active filter B's line currents; and (e) Active filter A's line currents.

the system using the proposed ideal model of the transformer shows good performance for this test condition. Thus, the effort to obtain a more accurate transformer model, which includes parasitics such as leakage inductances and parasitic capacitances, is not justified.



(a)

(b)

(c)

Fig. 9. Transformers with asymmetric parameters: (a) Line currents; (b) Single phase's load current for Unit A and B; and (c) Single phase AF's currents for Unit A and B.

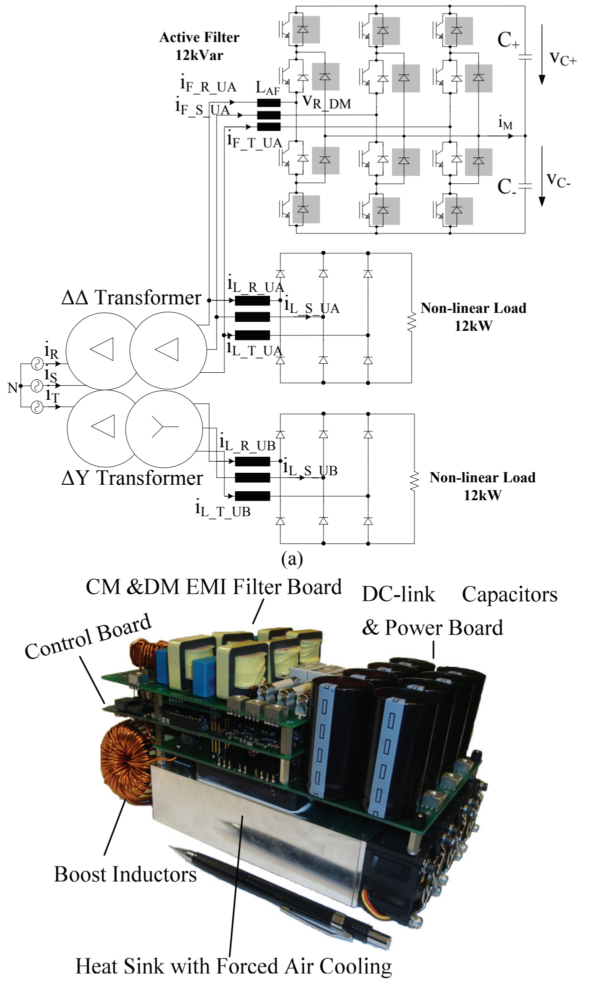
As can be observed in Fig. 8 and 9, the proposed transformer model can be used to adjust the current reference of the control of a typical active filter, without degrading its performance even in cases where the parameters of the transformer are asymmetric.

Note that the proposed model of the transformer can be used in a multi-pulse system configuration with one or more active filters. For the single active filter solution, all the reactive power, which the multi-pulse system could not eliminate, will be processed by this converter. For multiple AF solutions, all the reactive power is equally shared between the active filters.

III. EXPERIMENTAL VERIFICATION

In order to validate the proposed transformer model the circuit set-up shown in Fig. 10(a) was built. The transformer utilized to phase shift the primary to the secondary windings by 30 degrees is a Dy1 type transformer with turn ratio of $\sqrt{3}:1$ fed by a 400V line-to-line grid. The 12kVAr active filter shown in Fig. 10(b) is added on the Dd0 transformer secondary side to mitigate the remaining harmonics of the constructed 12 pulse system.

The 12 kVAr/48kHz active filter depicted in Fig. 10(b) uses three-level bridge-leg modules employing silicon carbide (SiC) Schottky diodes to enable highly efficient operation (gray diodes). A digital signal processing board with a TI DSP and a Lattice FPGA is used to implement the control strategy shown in Fig. 5 and also the vector modulation scheme described in [11]. The balance of the dc-link voltages is achieved by selecting one of the two available redundant zero vectors from the inner hexagon vectors [12]. Three boost inductors with an inductance value of 300µH are employed. In total, eight 470µF/450V electrolytic capacitors are arranged to obtain an equivalent dc link capacitance of 940µF. An EMI filter board complying with CISPR Class A for CM and DM emissions and an optimized heat sink have been designed. The power density of this active filter is 3.65kW/dm^3 and the system efficiency is around 96.3%.



(a)

(b)

Fig. 10. Experimental verification: (a) 12 pulse system + active filter circuit diagram; and (b) 12 *k*VAr 3- level shunt active filter.

Experimental results from the 12 pulse system employing the designed active filter are given in Fig. 11. In Fig. 11(a), one rectifier unit is set to deliver about 4kW to the load and the other unit about 4.5kW. In this case, the active filter processes only about 800VAr to allow sinusoidal line currents. The dynamic performance of the system is shown in Fig. 11(b), where a load step from imbalanced 8kW to a balanced 12kW operation takes place. The grid voltage and sinusoidal shaped line currents obtained after the load step are presented in Fig. 11(c). The main waveforms of the three level active filter can be seen in Fig. 11(d). The main waveforms for the grid synchronization based on SRF-PLL are shown in Fig. 11(e). Fig. 11(f) and 11(g) present the harmonic analysis of the line current for the equivalent 12 pulse system without and with active filter for the imbalanced load condition shown in Fig. 11(a), respectively.

As can be noted in Fig 11, the designed shunt active filter could efficiently compensate the current harmonics with order higher than the 7th order. In addition, it adjusted the 5th and 7th harmonics on the Dd0 secondary side to be of the same amplitude as the ones on the Dy1 secondary side . In this way, the 12 pulse system could considerably attenuate the 5th and 7th harmonics, and the studied system drained

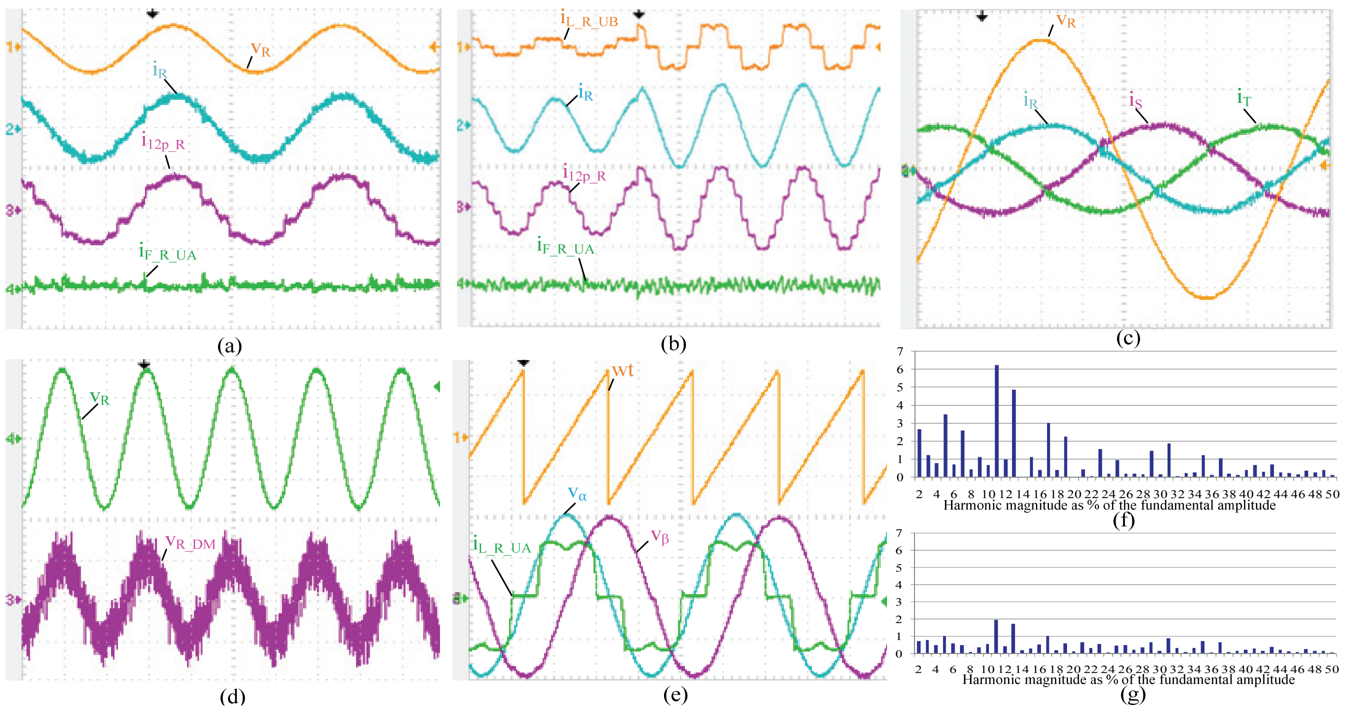


Fig. 11. 12 pulse system + active filter main waveforms: (a) Phase R grid voltage, line current, equivalent 12 pulse current, and active filter current; (b) Dynamic performance of the active filter for load step (7kW to 12kW); (c) System sinusoidal shaped line currents and grid voltage; (d) Three level active filter main waveforms; (e) Grid voltage synchronization main waveforms for SRF-PLL; (f) and (g) present the harmonic analysis of the line current for the 12 pulse system without and with active filter, respectively. For all figures the current waveforms are shown with 25A/div scale.

currents with sinusoidal shape. Therefore, the proposed transformer current model can be used to adjust the current reference of typical active filter controls, without degrading the system performance even in cases where the parameters of the 12 pulse transformer are asymmetric.

IV. CONCLUSION

This work presents two highly efficient ESP system configurations which comply with harmonic guidelines (e.g. IEEE 519). Distribution transformers are chosen to build a multi-pulse system and AFs are installed on the low voltage side of the transformer in order to use standard, low cost IGBTs and circuit components, which also enable a higher switching frequency/efficiency. The AFs are intended for high order harmonic-current-mitigation (>7th harmonic), and to balance, mainly, the 5th and 7th current harmonics, which can be effectively eliminated by the multi-pulse system. The ESP system becomes highly efficient because the active filters (AFs), only process about 10% of the total system apparent power.

A suitable control strategy for the proposed multi-pulse and active filter systems is presented. This strategy is based on the mathematical model of the distribution transformer which predicts and adjusts the line current on the MV side for the AF's current reference generation, by only sensing the currents of the ESP power supplies on the transformers' LV side. Due to the fact that only relatively simple calculations are necessary, delays on the reference signal processing are minimized, and control strategies, which are commonly used in AF solutions, can be adapted without degrading the overall performance of the active filter.

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