

# A Single-Phase Active Device for Power Quality Improvement of Electrified Transportation

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**Abstract** — A Transformerless Hybrid Series Active Filter (THSeAF) is proposed to enhance the power quality in single-phase systems with critical loads. This paper assists the energy management and power quality issues related to electric transportation, and focuses on improving electric vehicles loads connection to the grid. The control strategy is designed to prevent current harmonic distortions of non-linear loads to flow into the utility and corrects the power factor of this later. While, protecting sensitive loads from voltage disturbances, sags, and swells initiated by the power system, riddled of the series transformer, the configuration is advantageous for an industrial implementation. This polyvalent hybrid topology allowing harmonic isolation and compensation of voltage distortions could absorb or inject the auxiliary power to the grid. Beside practical analysis the paper also investigates on the influence of gains and delays in the real time controller stability. The simulations and experimental results presented in this work were carried out on a 2kVA laboratory prototype demonstrating the effectiveness of proposed topology.

**Index Terms** — Hybrid series active filter, current harmonics, power quality, electric vehicle, real-time control.

## I. INTRODUCTION

The forecast of future Smart Grids associated with electric vehicle charging stations has created a serious concern on all aspects of power quality of the power system, while widespread electric vehicles battery charging units [1, 2] have detrimental effects on power distribution system harmonic voltage levels [3]. On the other hand, the growth of harmonics fed from nonlinear loads like electric vehicle propulsion battery chargers [4, 5], which indeed have detrimental impacts on the power system and affect plant equipment, should be considered in the development of modern grids. Likewise, the increased rms and peak-value of the distorted current waveforms increase heating and losses and cause failure of the electrical equipment. Such phenomenon effectively reduces system efficiency and should properly been addressed [6, 7].

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Moreover, to protect the point of common coupling (PCC) from voltage distortions, using dynamic voltage restorer function is advised. A solution is to reduce the pollution of power electronics based loads directly at their source. Although several attempts are made for specific case study a generic solution is to be explored. There exist two types of active power devices to overcome described power quality issues. The first category are series active filters including hybrid type ones. They were developed to eliminate current harmonics produced by non-linear load from the power system. Series active filters are less scattered than shunt type of active filters [8, 9]. The advantage of series active filter compared to shunt type is the inferior rating of the compensator versus load nominal rating [10]. However, the complexity of the configuration and necessity of an isolation series transformer had decelerated their industrial application in distribution system. The second category was developed in concern of addressing voltage issues on sensitive loads. Commonly known as Dynamic voltage restorer (DVR), they have a similar configuration as of Series active filter. These two categories are different from each other in their control principle. This difference relies on purpose of their application in the system.

Hybrid series active filter (HSeAF) was proposed to address above aforementioned issues with only one combination. Hypothetically, they are capable to compensate current harmonics, ensuring a power factor correction, and eliminating voltage distortions at the PCC [11, 12]. These properties make it an appropriate candidate for power quality investments. The three-phase series active filters are well documented [13, 14], whereas limited research works reported the single-phase applications of series active filters in the literature. In this paper a single-phase transformerless-HSeAF is proposed and capable of cleanup the grid side connection bus bar from current harmonics generated by a non-linear load [15]. With a smaller rating up to 10%, it could easily replace the shunt active filter [16]. Furthermore, it could restore a sinusoidal voltage at the load point of common coupling.

Advantage of the proposed configuration is that non-linear harmonic voltage and current producing loads could be effectively compensated. The THSeAF is an alternative option to conventional power transferring converters in distributed generation systems with high penetration of renewable energy sources, where each phase can be controlled separately and could be operated independently of other phases [17]. This paper shows that the separation of a three-phase converter into single-phase H-bridge converters has allowed the elimination of the costly isolation transformer and promotes industrial application for filtering purposes. The setup has shown great ability to perform requested compensating tasks for correction

of current and voltage distortions, power factor correction, as well as voltage restoration on the load terminal [18].

This article is organized as follows: The system architecture is introduced in following section. Then the operation principle of the proposed configuration is explained. The third section is dedicated to the modeling and analysis of the control algorithm implemented in this work. The dc voltage regulation and its considerations are briefly explained and the voltage and current harmonic detection method is explicitly described. To evaluate the configuration and the control approach, some scenarios are simulated. Experimental results performed in laboratory are demonstrated to validate simulations. The paper is summarized with a conclusion and appendix where further mathematical developments are demonstrated.

## II. SYSTEM ARCHITECTURE

### A. System configuration

The transformerless hybrid series active filter shown in Fig.1 is composed of an H-bridge converter connected in series between the source and the load. A shunt passive capacitor ensures a low impedance path for current harmonics. A DC auxiliary source could be connected to inject power during voltage sags. The DC link energy storage system is described in [19]. The system is implemented for a rated power of 2200 VA. To ensure a fast transient response with sufficient stability margins over a wide range of operation, the controller is implemented on a dSPACE/dsp1103. The system parameters are identified in Table I. A variable source of 120 Vrms is connected to a 1.1 kVA non-linear load and a 998 VA linear load with a 0.46 power factor. The THSeAF is connected in series in order to inject the compensating voltage. On the DC side of the compensator, an auxiliary dc-link energy storage system is installed. Similar parameters are also applied for practical implementation.

TABLE I  
CONFIGURATION PARAMETERS

Symbol	Definition	Value
$v_s$	Line phase-to-neutral voltage	120 Vrms
$f$	System frequency	60 Hz
$R_{non-linear load}$	Load resistance	11.5 $\Omega$
$L_{non-linear load}$	Load inductance	20 mH
$P_L$	Linear load power	1 kVA
$PF$	Linear load power factor	46 %
$L_f$	Switching ripple filter inductance	5 mH
$C_f$	Switching ripple filter capacitance	2 $\mu$ F
$T_s$	dSPACE Synchronous sampling time	40 $\mu$ s
$f_{PWM}$	PWM frequency	5 kHz
$G$	Control gain for current harmonics	8 $\Omega$
$V_{DCref}^*$	VSI DC bus voltage of the THSeAF	70 V
$PI_G$	Proportional gain ( $K_p$ ), Integral gain ( $K_i$ )	0.025(4*), 10 (10*)

\* Adopted value for the experimental setup

HSeAFs are often used to compensate distortions of current type of non-linear loads. For instance, the distorted current and voltage waveforms of the non-linear system during normal operation and when the source voltage became distorted are depicted in Fig. 2. The THSeAF is bypassed and current harmonics flew directly into the grid. As one can perceive,

even during normal operation the current harmonics (with a Total Harmonic Distortion, THD of 12%) distort the PCC, resulting in voltage THD of 3.2%. The behavior of the system when the grid is highly polluted with 19.2% of THD is also illustrated. The proposed configuration could be solely connected to the grid with no need of a bulky and costly series injection transformer, making this topology capable of compensating source current harmonics and voltage distortion at the point of common coupling. Even if the number of switches has increased, the transformerless configuration is more cost-effective than any other series compensators, which generally uses a transformer to inject the compensation voltage to the power grid. The optimized passive filter is composed of a 5<sup>th</sup>, 7<sup>th</sup>, and a High-pass filters. The passive filter should be adjusted for the system upon load and government regulations. A comparison between different existing configurations is given in Table II. It is aimed to point out the advantages and disadvantages of the proposed configuration over the conventional topologies.

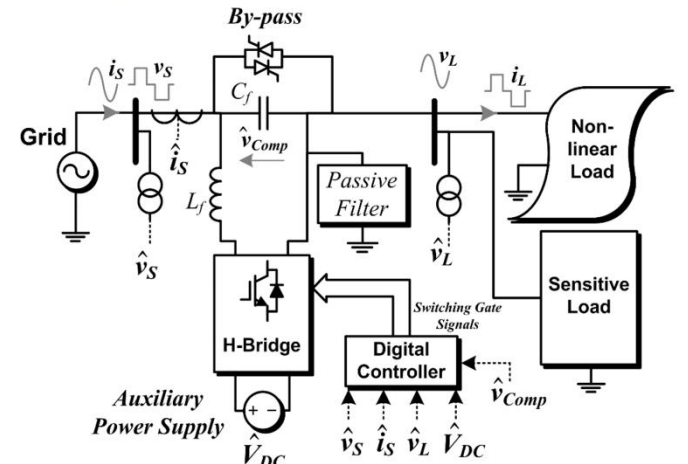
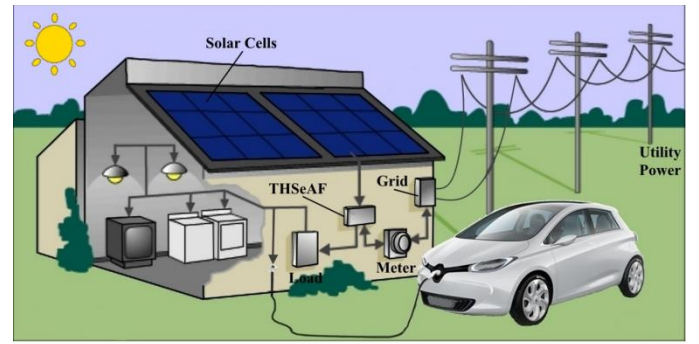


Fig. 1. a) Schematic of a single-phase smart load with the compensator installation, b) Electrical diagram of the THSeAF in a single-phase utility.

To emphasize the comparison Table fairly, equivalent single-phase of each configuration is considered in the evaluation. Financial production evaluation demonstrated a 45% reduction in components costs and considerable reduction in assembly terms as well.

### B. Operation principle

The series active filter represents a controlled voltage source (VSI). In order to prevent current harmonics  $i_{Lh}$  to drift into the source, this series source should present low impedance for the fundamental component and high impedance for all harmonics as shown in Fig. 3. The principle of such modeling is well documented in [20].

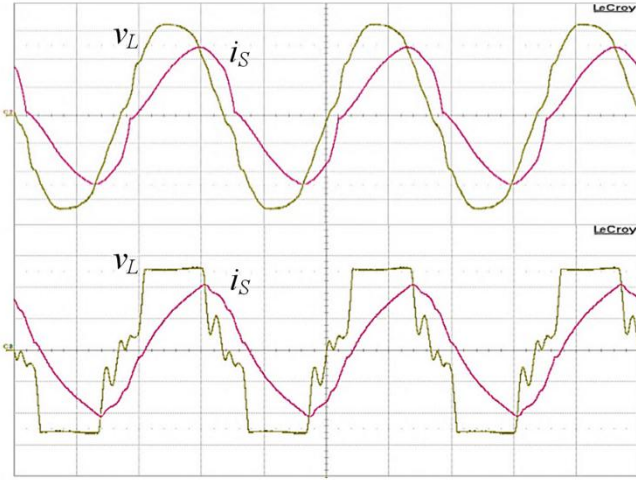


Fig. 2. Terminal voltage and current waveforms of the 2kVA single-phase system without compensator. a) Regular operation, b) Grid's voltage distortion (scales: 50 V/div for channel 1 and 10 A/div for channel 2).

The use of a well-tuned passive filter is then, mandatory to perform compensation of current issues and maintaining a constant voltage free of distortions at the load terminals. The behavior of the series active filter (SeAF) for a current control approach is evaluated from the phasor's equivalent circuit shown in Fig. 3. The non-linear load could be modeled by a resistance representing the active power consumed and a current source generating current harmonics. Accordingly, the impedance  $Z_L$  represents the non-linear load and the inductive load.

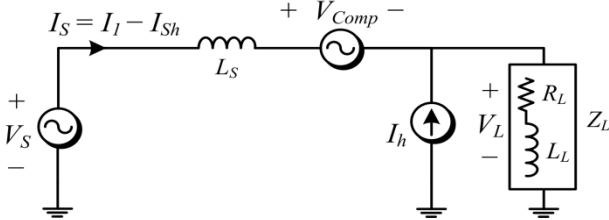


Fig. 3. THSeAF equivalent circuit for current harmonics.

The series active filter operates as an ideal controlled voltage source ( $V_{comp}$ ) having a gain ( $G$ ) proportional to the current harmonics ( $I_{sh}$ ) flowing to the grid ( $V_S$ ).

$$V_{comp} = G \cdot I_{sh} - V_{Lh} \quad (1)$$

This allows having individual equivalent circuit for the fundamental and harmonics:

$$V_{source} = V_{s1} + V_{sh} \quad , \quad V_L = V_{L1} + V_{Lh} \quad (2)$$

The source harmonic current could be evaluated.

$$V_{sh} = -Z_s \cdot I_{sh} + V_{comp} + V_{Lh} \quad (3)$$

$$V_{Lh} = Z_L(I_h - I_{sh}) \quad (4)$$

Combining (3) and (4) leads to (5).

$$I_{sh} = \frac{V_{sh}}{(G - Z_s)} \quad (5)$$

If gain  $G$  is sufficiently large ( $G \rightarrow \infty$ ), the source current will become clean of any harmonics ( $I_{sh} \rightarrow 0$ ). This will help improving the voltage distortion at the grid side. In this approach the THSeAF behaves as high impedance open circuit for current harmonics, while the shunt high pass filter tuned at the system frequency, creates a low-impedance path for all harmonics and open circuit for the fundamental; it also helps for power factor correction.

TABLE II  
SINGLE-PHASE COMPARISON OF THE THSeAF TO PRIOR HSeAFs

Definition	Proposed THSeAF	[21]	[22]	[12]
Injection Transformer	Non	2 per phase	1 per phase	1 per phase
# of semiconductor devices	4	8	4	4
# of DC link storage elements	1+Aux. Pow.	1	2	1+Aux. Pow.
AF rating to the load power	10-30%	10-30%	10-30%	10-30%
Size and weight, regarding the transformer, power switches, drive circuit, heat sinks, etc.	The Lowest	High	Good	Good
Industrial production costs	The Lowest	High	Low	Low
Power losses, including switching, conducting, and fixed losses	Low	Better	Low	Low
Reliability regarding independent operation capability	Good	Low	Good	Good
Harmonic correction of Current source load	Good	Good	Good	Low
Voltage Harmonic correction at load terminals	Good	Better	Good	Good
Power factor correction	Yes	Yes	Yes	No
Power injection to the grid	Yes	No	No	Yes

### III. MODELING AND CONTROL OF THE SINGLE-PHASE THSeAF

#### A. Average and Small-signal Modeling

Based on the average equivalent circuit of an inverter [23], the small-signal model of the proposed configuration can be obtained as of Fig. 4. Hereafter,  $d$  is the duty cycle of the upper switch during a switching period, whereas  $\bar{v}$  and  $\bar{i}$  denotes the average values in a switching period of the voltage and current of the same leg. The mean converter output voltage and current are expressed by (6) and (7) as follow.

$$\bar{v}_o = \frac{(2d-1)V_{dc}}{m} \quad (6)$$

$$\bar{i}_{DC} = m\bar{i}_f \quad (7)$$

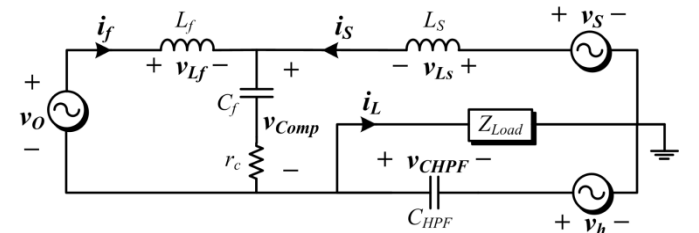


Fig. 4. Small-signal model of transformerless HSeAF in series between the Grid and the load.

Calculating the Thévenin equivalent circuit of the harmonic current source leads to the following assumption.

$$\bar{v}_h(j\omega) = \frac{-j\bar{i}_h}{C_{HPF}\omega_h} \quad (8)$$

If the harmonic frequency is high enough, it is possible to assume that there will be no voltage harmonics across the load. The state-space small-signal ac model could be derived by a linearized perturbation of averaged model as follow:

$$\dot{x} = Ax + Bu \quad (9)$$

Hence we obtain:

$$\frac{d}{dt} \begin{bmatrix} \bar{v}_{cf} \\ \bar{v}_{CHPF} \\ \bar{i}_s \\ \bar{i}_f \\ \bar{i}_L \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1/c_f & 1/c_f & 0 \\ 0 & 0 & 1/c_{HPF} & 0 & -1/c_{HPF} \\ -1/L_s & -1/L_s & -r_c/L_s & -r_c/L_s & 0 \\ -1/L_f & 0 & -r_c/L_f & -r_c/L_f & 0 \\ 0 & 1/L_L & 0 & 0 & -R_L/L_L \end{bmatrix} \begin{bmatrix} \bar{v}_{cf} \\ \bar{v}_{CHPF} \\ \bar{i}_s \\ \bar{i}_f \\ \bar{i}_L \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1/L_s & 0 & 1/L_s \\ 0 & m/L_f & 0 \\ 0 & 0 & -1/L_L \end{bmatrix} \times \begin{bmatrix} \bar{v}_s \\ \bar{v}_h \end{bmatrix} \quad (10)$$

And the output vector is:

$$y = Cx + Du \quad (11)$$

or

$$\begin{bmatrix} \bar{v}_{comp} \\ \bar{v}_L \end{bmatrix} = \begin{bmatrix} 1 & 0 & r_c & r_c & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \bar{v}_{cf} \\ \bar{v}_{CHPF} \\ \bar{i}_s \\ \bar{i}_f \\ \bar{i}_L \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \times \begin{bmatrix} \bar{v}_s \\ V_{DC} \\ \bar{v}_h \end{bmatrix} \quad (12)$$

By means of (10) and (12), the state-space representation of the model is obtained as shown in Fig. 4.

The transfer function of the compensating voltage versus the load voltage,  $T_{V_{CL}}(s)$ , and the source current,  $T_{CI}(s)$ , are developed in the appendix. Meanwhile, to control the active part independently the derived transfer function should be autonomous from the grid configuration. The transfer function  $T_{Vm}$  presents the relation between the output voltages of the converter versus the duty cycle of the first leg converter's upper switch.

$$T_V(s) = \frac{V_{comp}}{V_o} = \frac{r_c C_f s + 1}{L_f C_f s^2 + r_c C_f s + 1} \quad (13)$$

$$T_{Vm}(s) = \frac{V_{comp}}{m} = V_{DC} \cdot T_V(s) \quad (14)$$

Further detailed derivation of steady-state transfer functions are described in the section V.

A DC auxiliary source should be employed to maintain an adequate supply on the load terminals. During the sag or swell conditions, it should absorb or inject power to keep the voltage magnitude at the load terminals within a specified margin. However, if the compensation of sags and swells is less imperative, a capacitor could be deployed. Consequently, the DC-link voltage across the capacitor should be regulated as demonstrated in Fig.5.

### B. Voltage and Current Harmonic Detection

The outer-loop controller is used where a capacitor replaces the DC auxiliary source. This control strategy is well explained in the previous section. The inner-loop control strategy is based on an indirect control principle. A fast Fourier transformation

(FFT) was used to extract magnitude of the fundamental and its phase degree from current harmonics. The control gain  $G$  representing the impedance of the source for current harmonics, has a sufficiently level to clean the grid from current harmonics fed through the non-linear load.

The second PI controller used in the outer loop, was to enhance the effectiveness of the controller when regulating the DC bus. Thus a more accurate and faster transient response was achieved without compromising compensation behavior of the system. According to the theory, the gain  $G$  should be kept in a suitable level, preventing the harmonics flows into the grid [22, 24]. As previously discussed, for a more precise compensation of current harmonics, the voltage harmonics should also be considered. The compensating voltage for current harmonic compensation is obtained from (15).

$$v_{comp\_i}(t) = (-G\hat{i}_s + \hat{v}_L) - [-G\hat{i}_{s1} + v_{L1}] \cdot \sin(\omega_s t - \theta) \quad (15)$$

Hereby, as voltage distortion at the load terminals is not desired, the voltage sag and swell should also be investigated in the inner-loop. The closed loop equation (16) allows to indirectly maintain the voltage magnitude at load side equal to  $V_L^*$  as a predefined value, within acceptable margins.

$$v_{comp\_v} = \hat{v}_L - V_L^* \sin(\omega_s t) \quad (16)$$

The entire control scheme for the THSeAF presented in Fig. 5 was used and implemented in MATLAB/Simulink for real-time simulations and calculation of the compensating voltage. The real-time toolbox of dSPACE was used for compilation and execution on the dsp-1103 control board. The source and load voltages together with the source current are considered as system input signals. According to [25], an indirect control increases the stability of the system.

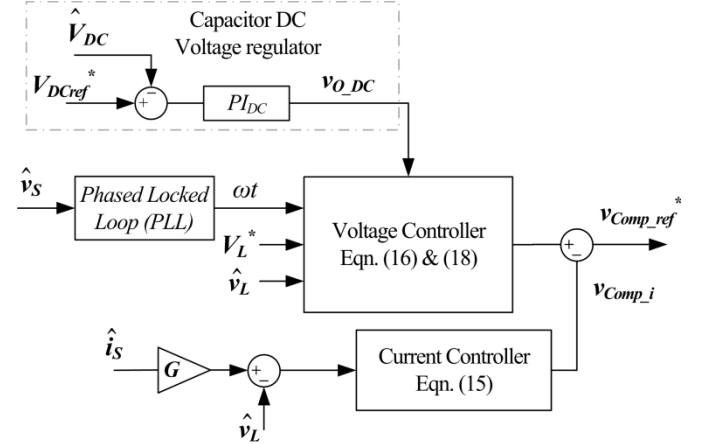


Fig. 5. Control system scheme of the active part.

The source current harmonics are obtained by extracting the fundamental component from the source current.

$$v_{comp\_ref}^* = v_{comp\_v} - v_{comp\_i} + v_{DC\_ref} \quad (17)$$

Where the  $v_{DC\_ref}$  is the voltage required to maintain the DC bus voltage constant.

$$v_{DC\_ref}(t) = V_{O\_DC} \cdot \sin(\omega_s t) \quad (18)$$

A phase-locked loop (PLL) was used to obtain the reference angular frequency ( $\omega_s$ ). Accordingly, the extracted current harmonic  $\hat{i}_{sh}$  contains a fundamental component synchronized with the source voltage in order to correct the power factor ( $PF$ ). This current represents the reactive power of the load. The gain  $G$  representing the resistance for harmonics converts current into a relative voltage. The



generated reference voltage  $v_{comp\_i}$  required to clean source current from harmonics is described in (15).

According to the presented detection algorithm, the compensated reference voltage  $v_{comp\_ref}^*$  is calculated. Thereafter, the reference signal is compared with the measured output voltage and applied to a PI controller to generate the corresponding gate signals as in Fig. 6.

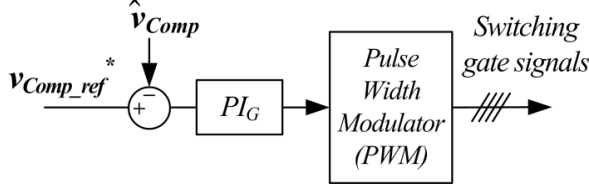


Fig. 6. Block diagram of THSeAF and PI controller.

### C. Stability Analysis for Voltage and Current Harmonics

The stability of the configuration is mainly affected by the introduced delay of a digital controller. This subsection studies the impact of the delay first on the inclusive compensated system according to works cited in the literature. Thereafter, its effects on the active compensator separated from the grid. Using purely inductive source impedance (see Fig.4) and the Kirchhoff's law for harmonic frequency components, (19) is derived. The delay time of digital controller, large gain  $G$  and the high stiffness of the system seriously affect the stability of the closed-loop controlled system.

$$I_{sh}(s) = \frac{V_{sh} - V_{comp} - V_{Lh}}{L_s s} \quad (19)$$

The compensating voltage including the delay time generated by the THSeAF in Laplace domain (see Eqn. (1)) is

$$v_{comp} = G \cdot I_{sh} \cdot e^{-\tau s} - V_{Lh} \quad (20)$$

Considering (19) and (20), the control diagram of the system with delay is obtained as in Fig. 7.

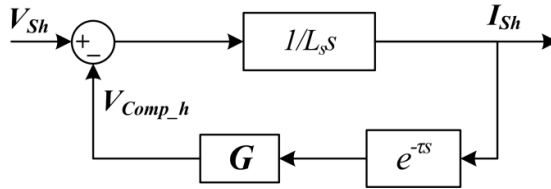


Fig. 7. The control diagram of the system with delay.

For the sake of simplicity, overall delay of the system is assumed to be a constant value  $\tau$ . Therefore, the open-loop transfer function is obtained.

$$G(s) = \frac{G}{L_s s} e^{-\tau s} \quad (21)$$

From the Nyquist stability criterion, the stable operation of the system must satisfy the following condition:

$$G < \frac{\pi L_s}{2\tau} \quad (22)$$

A system with a typical source inductance  $L_s$  of 250  $\mu$ H and a delay of 40  $\mu$ s is considered stable according to (22), when the gain  $G$  is smaller than 10 $\Omega$ . Experimental results confirm the stability of system presented in this work. Moreover, the influence of the delay on the control algorithm should also be investigated. According to the transfer functions (13) and (14), the control of the active part is affected by the delay introduced by the digital controller. Thus, assuming an ideal switching characteristic for the IGBTs, the closed-loop system for the active part controller is shown in Fig. 8.

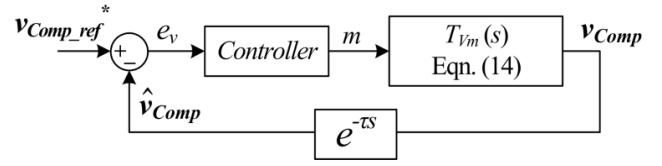


Fig. 8. Closed-loop control diagram of the Active filter with a constant delay time  $\tau$ .

The open loop transfer function in Fig. 8 turns to (23), where, the  $\tau$  is the delay time initiated by the digital controller.

$$F(s) = PI_G \cdot T_{Vm} \cdot e^{-\tau s} = \frac{(r_c C_f V_{DC} s + V_{DC}) \cdot (K_p s + K_i) e^{-\tau s}}{s \cdot (L_f C_f s^2 + r_c C_f s + 1)} \quad (23)$$

A PI controller with system parameters described in Table I demonstrate a smooth operation in the stable region. By means of MATLAB the behavior of the system's transfer function  $F(s)$  is traced in Fig. 9. The Root Locus and the Bode diagram of the compensated open-loop system demonstrate a gain margin of 8.06 dB and a phase margin of 91 degree. Furthermore, for an extra theoretical investigation, the influence of the delay on the load voltage could also be evaluated with regards to the transfer function  $T_{V_{LS}}(s)$  described in the appendix.

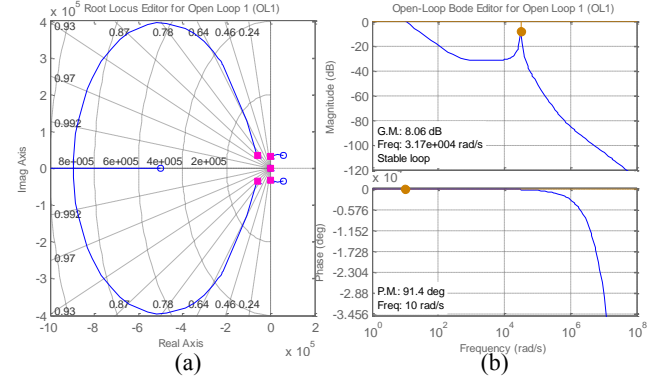


Fig. 9. Compensated open-loop system with delay time of 40  $\mu$ s. (a) Root Locus diagram. (b) Bode diagram.

## IV. SIMULATIONS AND EXPERIMENTAL RESULTS

The proposed Transformerless-HSeAF configuration was simulated in MATLAB/Simulink using discrete time steps of  $T_s = 10 \mu$ s. A dSPACE/dsp1103 was used for the fast control prototyping. To ensure an error free and fast implementation, the complete control loop was executed every 40  $\mu$ s. The parameters are identified in Table I.



Fig. 10. Transformerless-HSeAF prototype used for experiments.

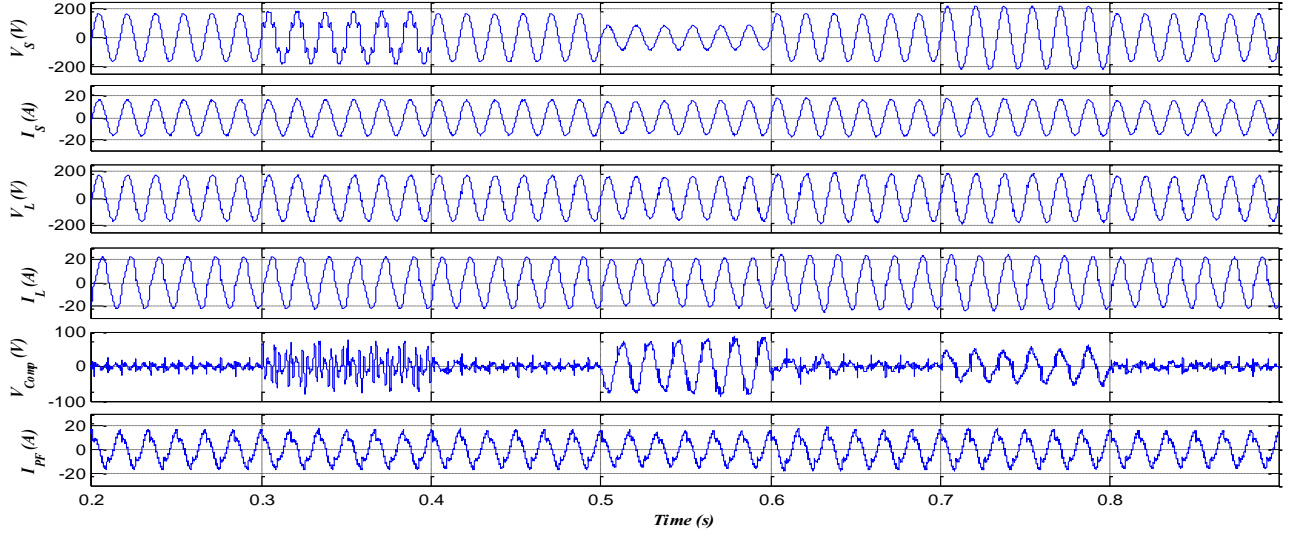


Fig. 11. Simulation of the system with the THSeAF compensating current harmonics and voltage regulation. (a) Source voltage  $v_s$ , (b) source current  $i_s$ , (c) Load voltage  $v_L$ , (d) load current  $i_L$ , (e) Active-filter voltage  $V_{Comp}$ , (f) Harmonics current of the passive filter  $i_{pf}$ .

The combination of a single-phase non-linear load and a linear load with a total rated power of 2 kVA with a 0.74 lagging power factor is applied for laboratory experiments and simulations. For experiments and simulations, a 2 kVA, 120 Vrms, and 60 Hz variable source is used. THSeAF connected in series to the system compensates the current harmonics and voltage distortions. The complete experimental system is demonstrated in Fig. 10.

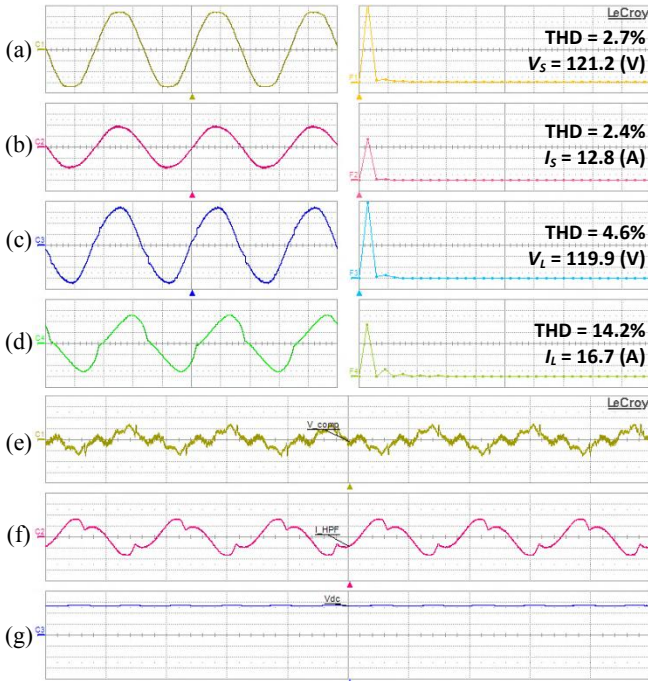


Fig. 12. Experimental wave forms and harmonic spectrum under steady-state sinusoidal grid voltage. (a) Source voltage  $v_s$  [50V/div], (b) source current  $i_s$  [10A/div], (c) load terminal voltage  $v_L$  [50V/div], (d) load current  $i_L$  [10A/div], (e) THSeAF voltage  $v_{Comp}$  [20V/div], (f) passive filter current  $i_{pf}$  [10A/div], (g) DC voltage  $v_{DC}$  [50V/div].

A gain  $G = 8 \Omega$  equivalent to 1.9 p.u. was used to control current harmonics. As mentioned earlier, the capability of operation with low dc voltage is considered as one of the main advantages of the proposed configuration. For this experiment

it is maintained at 130 Vdc. During a grid's voltage distortion, the compensator regulates the load voltage magnitude, compensates current harmonics and corrects the power factor. The simulated results of the THSeAF illustrated in Fig. 11, demonstrates improvement in the source current THD. The load terminal voltage  $V_L$  THD is 4.3% while, source voltage is highly distorted (THD  $V_s = 25\%$ ).

The grid is cleaned of current harmonics with a UPF operation and the THD is reduced to less than 1% in normal operation and less than 4% during grid perturbation. While the series controlled source clean the current of harmonic components, the source current is forced to be in phase with the source voltage. The series compensator has the ability to slide the load voltage in order for the power factor to reach unity. Furthermore, the series compensator could control the power flow between two PCCs.

Experimental results obtained in laboratory corroborate the successful operation of the THSeAF shown in simulations. Fig. 12 shows the compensator during steady state operating with parameters described in Table I. The source current became sinusoidal and the load voltage regulated at rated 120 Vrms. The source current is in phase with the utility voltage achieving a unity power factor correction. The grid supplies 1.545kVA at a PF equal to 0.99, while the load consumes 2 kVA with a PF of 0.75.

TABLE III  
LABORATORY MEASURED VALUE AND POWER FLOW ANALYSIS

	Load		Grid Utility (Source)	
Measures	Voltage (V), $V_L$	Current (A), $I_L$	Voltage (V), $V_S$	Current (A), $I_S$
THD (%)	4.6	14.2	2.7	2.4
Fund. (rms)	119.9	16.7	121.2	12.8
Active power, P (W)	1499.7		1544.4	
Reactive power, Q (var)	1284.5		10.6	
Power, S (VA)	1998.6		1545.2	
Power Factor, PF	0.75		0.99	
Compensator, THSeAF	$S_{Comp} = +44W - j1274var$			

The compensator shows high efficiency in normal operation where the total compensator losses including



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switching, inductors resistances and damping resistances are equal to 44 W which is less than 2.5% of the system rated power. The power flow and THD of measured values are depicted in table III for case demonstrated in Fig. 12.

The experimented results illustrate a high fidelity with results observed in simulation. Therefore, the system is subjected to sag and swells initiated from the utility source as shown in following figures. While cleaning the source current from harmonics and correcting the power factor the compensator regulates the load terminal voltage. Clarified in section III, the auxiliary source provides necessary amount of power to maintain the supply at the load terminals despite variation in the source magnitude. The behavior of the proposed compensator during dynamic load variation could be depicted from Fig. 14, where the load is suddenly changed.

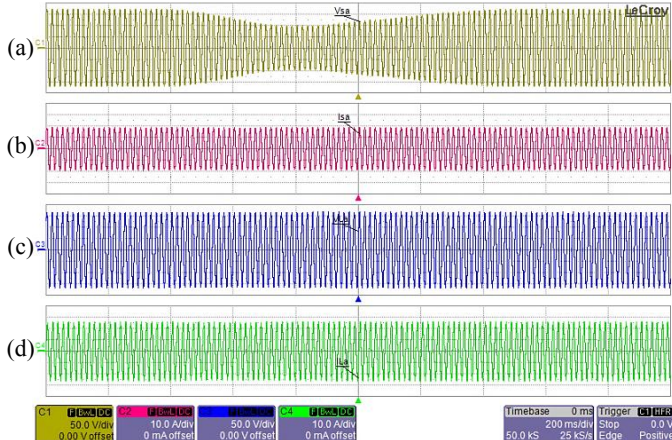


Fig. 13. Wave forms during a variation of the source voltage. (a) Source voltage  $v_s$  [50V/div], (b) source current  $i_s$  [10A/div], (c) load PCC voltage  $v_L$  [50V/div], (d) load current  $i_L$  [10A/div].

The THSeAF reacts instantly to this variation and do not interfere its operation functionality. Meanwhile, it is normal to observe a slight transient voltage variation depending on the momentum of the load disengagement or connection.

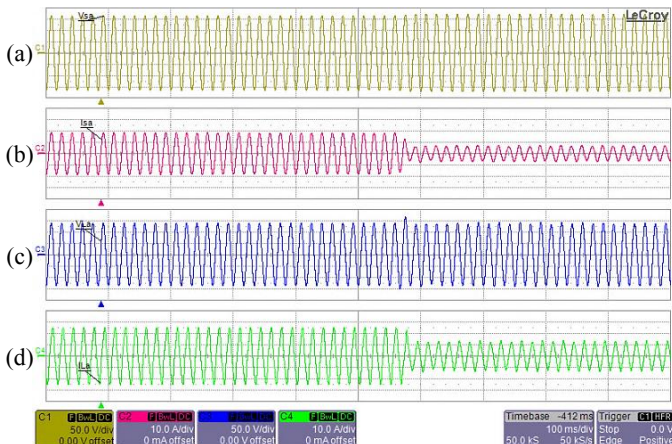


Fig. 14. Wave forms during a dynamic load variation. (a) Source voltage  $v_s$  [50V/div], (b) source current  $i_s$  [10A/div], (c) load PCC voltage  $v_L$  [50V/div], (d) load current  $i_L$  [10A/div].

To evaluate the compensator during utility perturbation, the power source became distorted as depicted in Fig. 15. The source current became cleaned of the majority of harmonics available in the load current and has a unity power factor. The

THSeAF prevent existing perturbation on the grid's voltage to propagate on the load PCC. It protects sensitive loads and maintains a sinusoidal and regulated voltage across the point of common coupling of loads with a 3.9% of distortion. Moreover, in a worst possible scenario, the already distorted utility's voltage is subjected to voltage magnitude variation. Thus, the compensator should also inject power to maintain the load PCC voltage regulated at desired level.

During voltage sag and swell the auxiliary source supplies the difference of power to maintain the magnitude of the load side voltage regulated. The harmonic content and THD factor of the source utility and load PCC presented shows dramatic improvements in THD while the load draw polluted current waveforms. Furthermore, although the grid's voltage is polluted the compensator in a hybrid approach regulates and maintains a harmonics-free load's voltage.

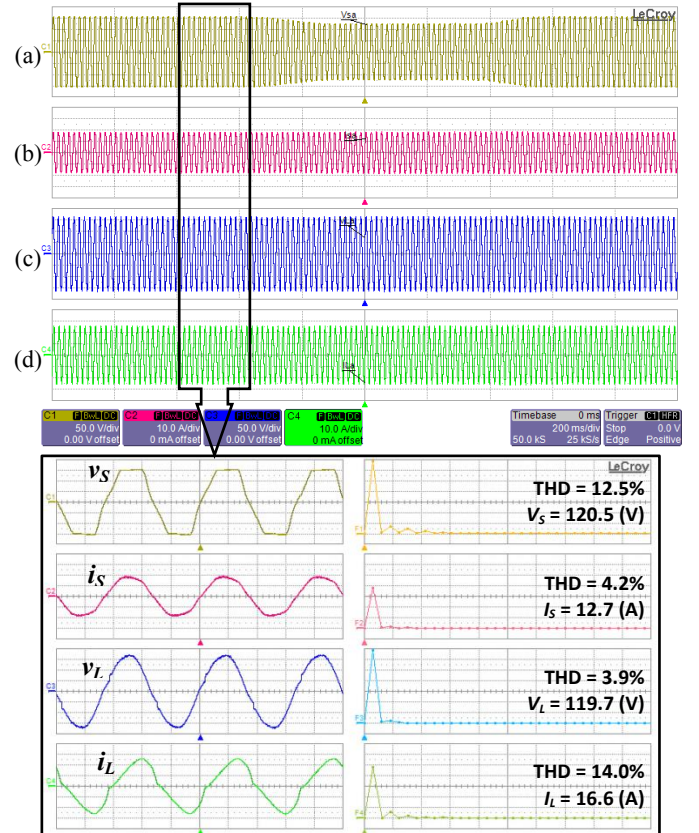


Fig. 15. Experimental wave forms under utility voltage distortion and a prolonged sags. (a) Utility source voltage  $v_s$  [50V/div], (b) Utility current  $i_s$  [10A/div], (c) load PCC voltage  $v_L$  [50V/div], (d) load current  $i_L$  [10A/div].

## V. APPENDIX

For the sake of simplicity the resistance  $r_c$  of the switching capacitor filter  $C_f$  is neglected and the inductance  $L_f$  has an ideal behavior.

### A. Relationship of load voltage ( $V_L$ ) and grid voltage ( $V_S$ )

$$T_{V_{LS}}(s) = \frac{V_L(s)}{V_S(s)} = \frac{Z_{Load}}{L_S + Z_{out} + Z_{Load}} = \frac{L_f L_L C_f s^3 + L_f R_L C_f s^2 + L_L s + R_L}{A + B + C + D + E + F}$$

$$A = L_f L_L L_S C_f C_{HPPF} s^5, \quad B = L_f L_S R_L C_f C_{HPPF} s^4$$

$$C = (L_f L_L C_f + L_f L_L C_{HPPF} + L_f L_S C_f + L_L L_S C_{HPPF}) s^3$$

$$D = (L_f R_L C_f + L_f R_L C_{HFPF} + L_S R_L C_{HFPF}) s^2$$

$$E = (L_f + L_L + L_S) s, \quad F = R_L$$

### B. Relation between load voltage ( $V_L$ ) and compensating voltage ( $V_{Comp}$ )

$$T_{V_{CL}}(s) = \frac{V_{Comp}}{V_L} = \frac{Z_{out}}{Z_{Load}} =$$

$$\frac{L_f L_L C_{HFPF} s^3 + L_f R_L C_{HFPF} s^2 + L_f s}{L_f L_L C_f s^3 + L_f R_L C_f s^2 + L_L s + R_L}$$

## VI. SUMMARY

In this paper a Transformerless-HSeAF for power quality improvement was developed and tested. The paper highlighted the fact that with the ever increase of non-linear loads and higher exigency of consumer for a reliable supply, concrete actions should be taken into consideration for future Smart Grids in order to smoothly integrate electric cars battery chargers to the grid. The key novelty of the proposed solution is that the proposed configuration could improve power quality of the system in more general way by compensating a wide range of harmonics current. Even though, it can be seen the THSeAF regulates and improves the PCC voltage. Connected to a renewable auxiliary source, the topology is able to counteract actively to the power flow in the system. This essential capability is required to ensure a consistent supply for critical loads. Behaving as high-harmonic impedance, it cleans the power system and ensures a unity power factor. The theoretical modeling of the proposed configuration was investigated. The proposed transformerless configuration was simulated and experimentally validated. It was demonstrated that this active compensator responds properly to source voltage variations by providing a constant and distortion-free supply at load terminals. Furthermore, it eliminates source harmonic currents and improves power quality of the grid without the usual bulky and costly series transformer.

## VII. ACKNOWLEDGMENT

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