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Control and Design of a Single-Phase Active Device for Power Quality Improvement of Electrified Transportation

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Abstract*—A transformerless hybrid series active filter 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 vehicle load connection to the grid. The control strategy is designed to prevent current harmonic distortions of nonlinear 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, ridded of the series transformer, the configuration is advantageous for an industrial implementation. This polyvalent hybrid topology allowing the harmonic isolation and compensation of voltage distortions could absorb or inject the auxiliary power to the grid. Aside from practical analysis, this paper also investigates on the influence of gains and delays in the real-time controller stability. The simulations and experimental results presented in this paper were carried out on a 2-kVA laboratory prototype demonstrating the effectiveness of the proposed topology.*

Index Terms*—Current harmonics, electric vehicle, hybrid series active filter (THSeAF), power quality, 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 vehicle 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 the failure of the electrical equipment. Such phenomenon effectively reduces system efficiency and should have properly been addressed [6], [7].

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

The hybrid series active filter (THSeAF) was proposed to address the aforementioned issues with only one combination. Hypothetically, they are capable to compensate current harmonics, ensuring a power factor (PF) correction and eliminating voltage distortions at the PCC [11], [12]. These properties make it an appropriate candidate for power quality investments. The three-phase SeAFs are well documented [13], [14], whereas limited research works reported the single-phase applications of SeAFs in the literature. In this paper, a single-phase transformerlessTHSeAF is proposed and capable of cleaning up the grid-side connection bus bar from current harmonics generated by a nonlinear 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 PCC/

The advantage of the proposed configuration is that nonlinear harmonic voltage and current producing loads could be effectively compensated. The transformerless hybrid series active filter (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 Hbridge converters has allowed the elimination of the costlyisolation transformer and promotes industrial application for filtering purposes. The setup has shown great ability to perform requested compensating tasks for the correction of current and voltage distortions, PF correction, and voltage restoration on the load terminal [18].

The contemporary container crane industry, like many other industry segments, is often enamored by the bells and whistles, colorful diagnostic displays, high speed performance, and levels of automation that can be achieved. Although these features and their indirectly related computer based enhancements are key issues to an efficient terminal operation, we must not forget the foundation upon which we are building. Power quality is the mortar which bonds the Foundation blocks. Power quality also affects terminal operating economics, crane reliability, our environment, and initial investment in power distribution systems to support new crane installations. To quote the utility company newsletter which accompanied the last monthly issue of my home utility billing: ‘Using electricity wisely is a good environmental and business practice which saves you money, reduces emissions from generating plants, and conserves our natural resources.’ As we are all aware, container crane performance requirements continue to increase at an astounding rate. Next generation container cranes, already in the bidding process, will require average power demands of 1500 to 2000 kW – almost double the total average demand three years ago. The rapid increase in power demand levels, an increase in container crane population, SCR converter crane drive retrofits and the large AC and DC drives needed to power and control these cranes will increase awareness of the power quality issue in the very near future

POWER QUALITY PROBLEMS

For the purpose of this article, we shall define power quality problems as: ‘Any power problem that results in failure or misoperation of customer equipment, Manifests itself as an economic burden to the user, or produces negative impacts on the environment.’

When applied to the container crane industry, the power issues which degrade power quality include:

• Power Factor
• Harmonic Distortion
• Voltage Transients
• Voltage Sags or Dips
• Voltage Swells

The AC and DC variable speed drives utilized on board container cranes are significant contributors to total harmonic current and voltage distortion. Whereas SCR phase control creates the desirable average power factor, DC SCR drives operate at less than this. In addition, line notching occurs when SCR’s commutate, creating transient peak recovery voltages that can be 3 to 4 times the nominal line voltage depending upon the system impedance and the size of the drives. The frequency and severity of these power system disturbances varies with the speed of the drive. Harmonic current injection by AC and DC drives will be highest when the drives are operating at slow speeds. Power factor will be lowest when DC drives are operating at slow speeds or during initial acceleration and deceleration periods, increasing to its maximum value when the SCR’s are phased on to produce rated or base speed. Above base speed, the power factor essentially remains constant. Unfortunately, container cranes can spend considerable time at low speeds as the operator attempts to spot and land containers. Poor power factor places a greater kVA demand burden on the utility or engine-alternator power source. Low power factor loads can also affect the voltage stability which can ultimately result in detrimental effects on the life of sensitive electronic equipment or even intermittent malfunction. Voltage transients created by DC drive SCR line notching, AC drive voltage chopping, and high frequency harmonic voltages and currents are all significant sources of noise and disturbance to sensitive electronic equipment

II. SYSTEM ARCHITECTURE

A. System Configuration

The THSeAF 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.

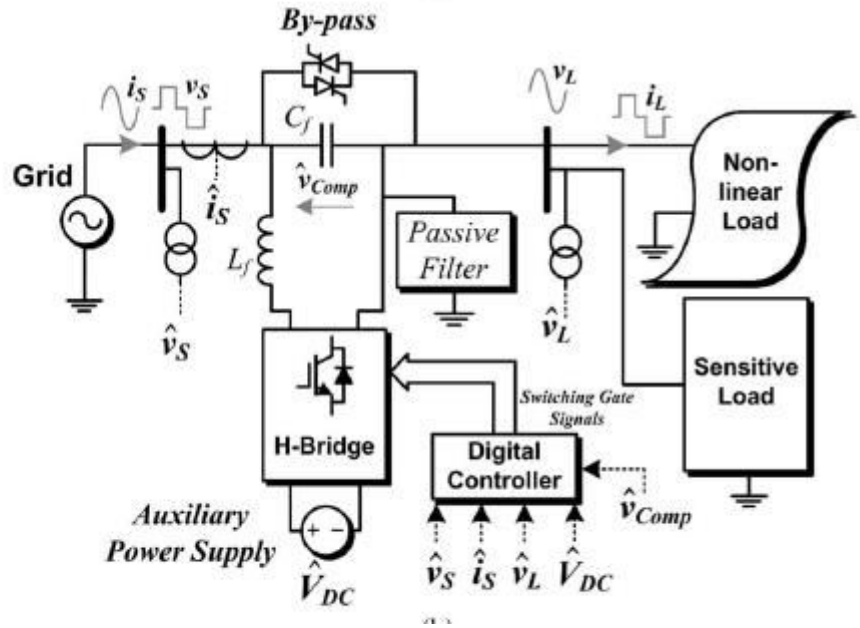

Fig.1.Electrical diagram of the THSeAF in a single-phase utility.

The system parameters are identified in Table I. A variable source of 120 Vrms is connected to a 1.1-kVA nonlinear load and a 998-VA linear load with a 0.46 PF. 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.

Symbol	Definition	value
Vs	Line phase to neutral voltage	120 Vrms
F	System frequency	60 hz
Rload	Load resistance	11.5 ohm
Lload	Load inductance	20mH
PL	Linear load power	1KVA
PF	Linear load power factor	46%
Lf	Switching ripple filterinductance	5mH
Cf	Switching ripple filter capacitance	2 microF
Ts	dSPACE synchronous sampling time	40 micro sec
Fpwm	PWM frequency	5Khz
G	Control gain for current hormonics	8ohm
VthseSf	VSI bus voltage of THSeAF	70V
Pig	Proportional gain integral gain	0.025(4*)

Table 1 Configuration parameters

THSeAFs are often used to compensate distortions of the current type of nonlinear loads. For instance, the distortedcurrent and voltage waveforms of the nonlinear system during normal operation and when the source voltage became distorted are depicted in Fig. 2. The THSeAF is bypassed, and current harmonics flowed 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 a 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 PCC. Even if the number of switches has increased, the transformer less 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 5th, 7th, and highpass 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.

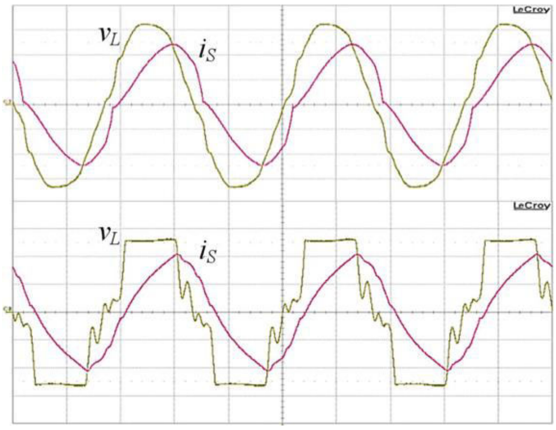

Fig. 2. Terminal voltage and current waveforms of the 2-kVA single phase system without compensator.

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

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
Dc link storage element	1+aux power	1	2	1+aux power
AF rating to the load power	10-30%	10-30%	10-30%	10-30%
Size and weight,regarding the transformer, power switches, dive circuit and heat sink	The lowest	High	good	good
Industrial production cost	The lowest	High	Low	low
Power losses including switching conduction 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

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

B. Operation Principle

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

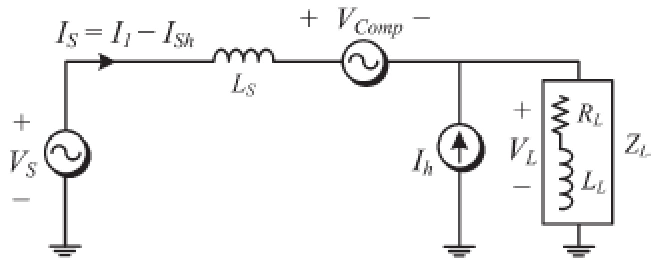

Fig. 3. THSeAF equivalent circuit for current harmonics

The SeAF operates as an ideal controlled voltage source (V comp) having a gain ($\boldsymbol{G}$) proportional to the current harmonics (Ish) flowing to the grid (Vs)

Vcomp= $G.Ish - VLh$……. (1)

This allows having individual equivalent circuit for the fundamental and harmonics

Vsource= $Vs1 + Vsh$, $VL = VL1 + VLh$. ….(2)

The source harmonic current could be evaluated

$Vsh = - Zs.Ish + V$comp$+ VLh$……………….. (3)

$VLh = ZL(Ih - Ish)$. ………………………….(4)

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

$Ish = Vsh(G - Zs)$……………………..(5)

If gain $\boldsymbol{G}$ is sufficiently large ($G \rightarrow \infty$), the source current will become clean of any harmonics ($Ish \rightarrow 0$). This will

help improve 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 PF correction.

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 in Fig. 4. Hereafter, d is the duty cycle of the upper switch during a switching period, whereas $\bar{v}$ and $\bar{i}$denote 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 follows:

$\bar{v}O$= (2d − _ __ 1_)VDC …………………………(6)

where the ($2d - 1$) equals to m, then $\bar{i}$ DC = $m\bar{i}f$ ……………………………………(7)

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

$\bar{v}h(j\omega) = -j\bar{i}hCHPF \cdot \omega h$ …………. (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 the averaged model as follows:

$\dot{x} = Ax + Bu$………… (9)

Hence, we obtain

$$\frac{d}{dt}\begin{bmatrix}\bar{v}_{Cf}\\ \bar{v}_{CHPF}\\ \bar{i}_S\\ \bar{i}_f\\ \bar{i}_L\end{bmatrix} = \begin{bmatrix}0 & 0 & \frac{1}{C_f} & \frac{1}{C_f} & 0\\ 0 & 0 & \frac{1}{C_{HPF}} & 0 & -1/C_{HPF}\\ -1/L_S & -1/L_S & -r_c/L_S & -r_c/L_S & 0\\ -1/L_f & 0 & -r_c/L_f & -r_c/L_f & 0\\ 0 & \frac{1}{L_L} & 0 & 0 & -R_L/L_L\end{bmatrix} \times \begin{bmatrix}\bar{v}_{Cf}\\ \bar{v}_{CHPF}\\ \bar{i}_S\\ \bar{i}_f\\ \bar{i}_L\end{bmatrix} + \begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ \frac{1}{L_S} & 0 & \frac{1}{L_S}\\ 0 & \frac{m}{L_f} & 0\\ 0 & 0 & -1/L_L\end{bmatrix} \times \begin{bmatrix}\bar{v}_S\\ V_{DC}\\ \bar{v}_h\end{bmatrix}. \quad (10)$$

Moreover, the output vector is

$y = Cx + Du$……. (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.

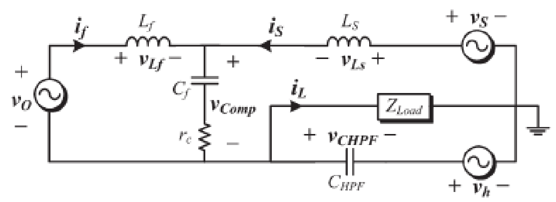

Fig. 4. Small-signal model of transformerlessTHSeAF in series between the grid and the load.

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.

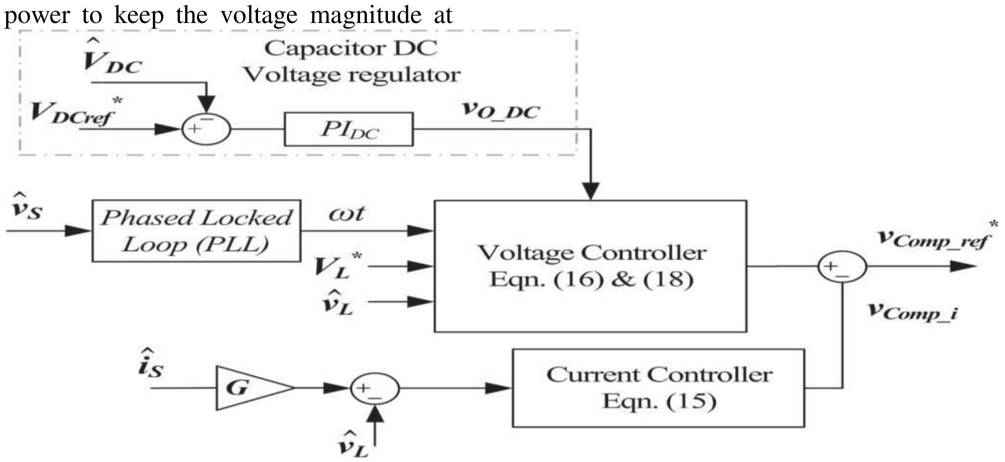

Fig. 5. Control system scheme of the active part.

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 was used to extract the 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 sufficient level to clean the grid from current harmonics fed through the nonlinear load.

The second proportional integrator (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 the compensation behavior of the system. According to the theory, the gain ***G*** should be kept in a suitable level, preventing the harmonics from flowing into the grid [22], [24]. As previously discussed, for a more precise compensation of current harmonics, the voltage harmonics should also be considered

C. *Stability Analysis for Voltage and Current Harmonics*

The stability of the configuration is mainly affected by theintroduced delay of a digital controller. This section 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 is separated from the grid. Using purely inductive source impedance (see Fig. 4) and Kirchhoff's law for harmonic frequency components, (19) is derived.

A *PI* controller with system parameters described in Table I demonstrates 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◦.

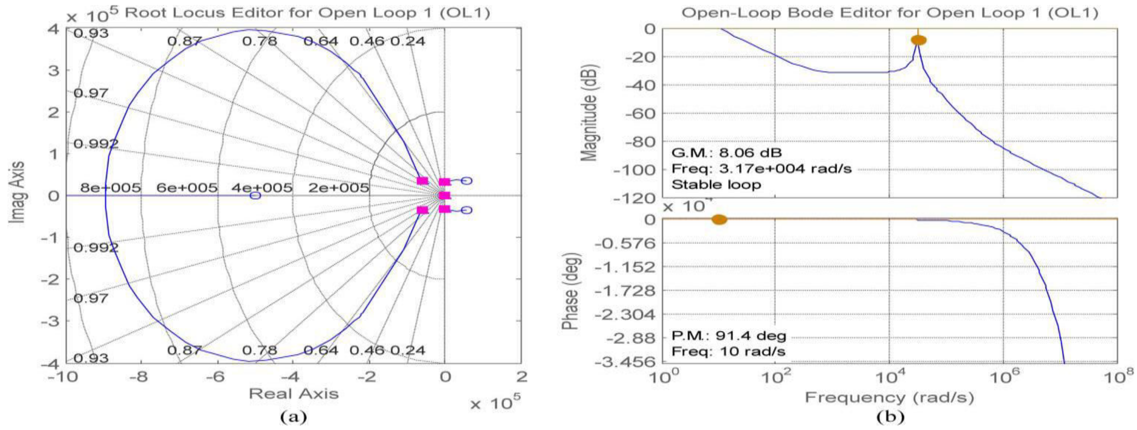

Fig. 9. Compensated open-loop system with delay time of 40 μs. (a) Root locus diagram. (b) Bode diagram.

IV.SIMULATIONS AND EXPERIMENTAL RESULTS

The proposed transformerless-THSeAF configuration was simulated in MATLAB/Simulink using discrete time steps of Ts= 10 μs. 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 μs. The parameters are identified in Table I.

The combination of a single-phase nonlinear load and a linear load with a total rated power of 2 kVA with a 0.74 lagging PF is applied for laboratory experiments and simulations. For experiments and simulations, a 2-kVA 120-Vrms 60-Hz variable source is used. THSeAF connected in series to the system compensates the current harmonics and voltage distortions. A gain $\boldsymbol{G}$ = 8 Ω 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 PF. The simulated results of the TTHSeAF illustrated in Fig. 11 demonstrates improvement in the source current THD. The load terminal voltage VL THD is 4.3%, while the source voltage is highly distorted (THD VS = 25%). The grid is cleaned of current harmonics with a unity power factor (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 cleans 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 PF to reach unity. Furthermore, the series compensator could control the power flow between two PCCs.

The THSeAF reacts instantly to this variation and does 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. To evaluate the compensator during utility perturbation, the power source became distorted as depicted in Fig. 12. The source current became cleaned of the majority of harmonics available in the load current and has a unity PF. The THSeAF prevents 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 PCC 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 the desired level

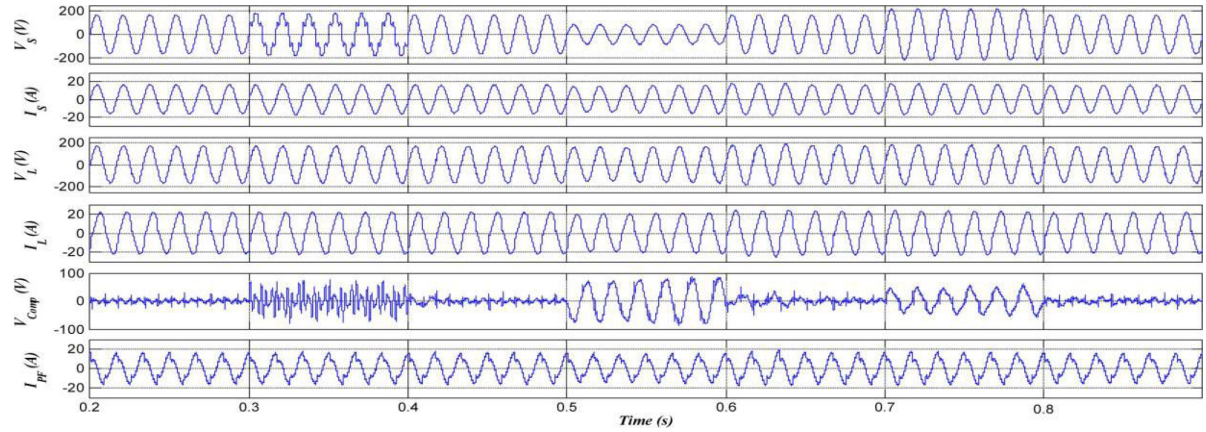

Fig. 11. Simulation of the system with the THSeAF compensating current harmonics and voltage regulation. (a) Source voltage *vS*, (b) source current *iS*, (c) load voltage *vL*, (d) load current *iL*, (e) active-filter voltage *V*Comp, and (f) harmonics current of the passive filter *I*pf

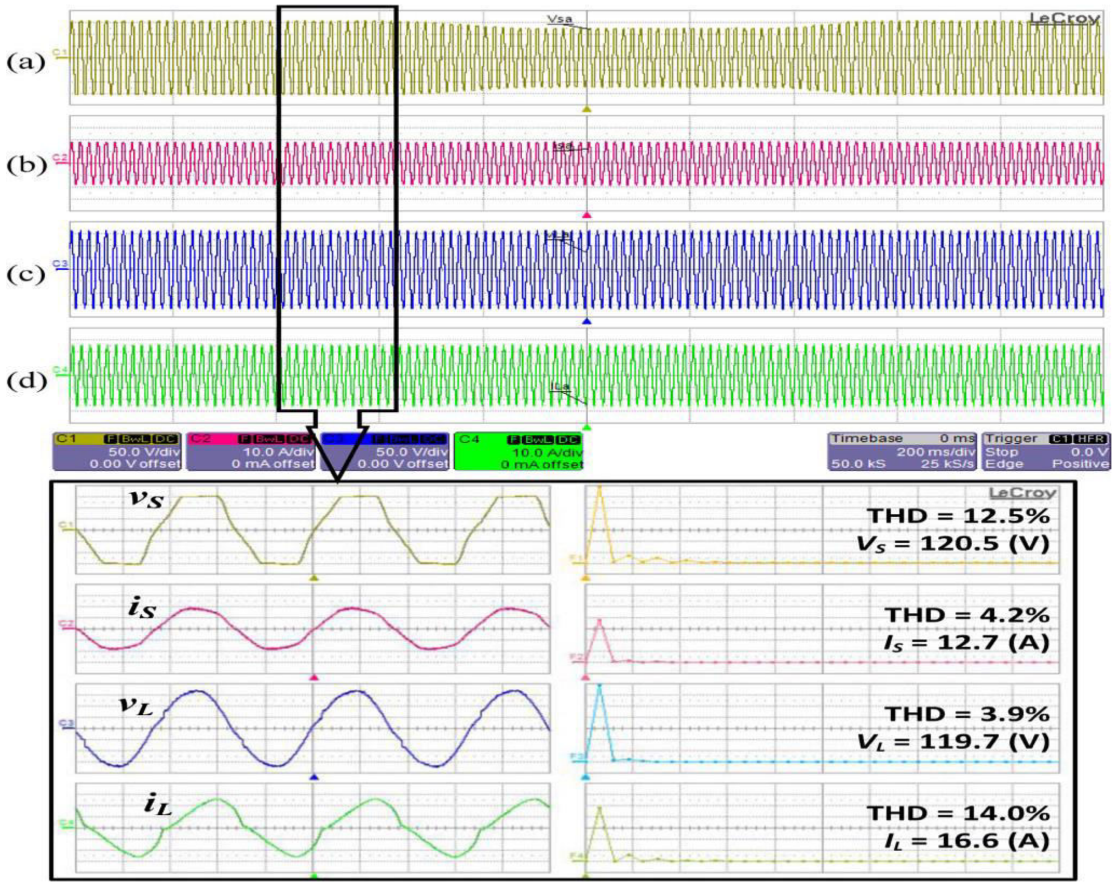

Fig. 12. Experimental waveforms under utility voltage distortion and prolonged sags. (a) Utility source voltage *vS*[50 V/div], (b) utility current *iS*[10 A/div], (c) load PCC voltage *vL*[50 V/div], and (d) load current *iL* [10 A/div]

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 show dramatic improvements in THD, while the load draws polluted current waveforms. Furthermore, although the grid's voltage is polluted, the compensator in a hybrid approach regulates and maintains a harmonic-free load voltage.

V. CONCLUSION

In this paper, a transformerlessTHSeAF for power quality improvement was developed and tested. The paper highlighted the fact that, with the ever increase of nonlinear loads and higher exigency of the consumer for a reliable supply, concrete actions should be taken into consideration for future smart grids in order to smoothly integrate electric car battery chargers to the grid. The key novelty of the proposed solution is that the proposed configuration could improve the power quality of the system in a more general way by compensating a wide range of harmonics current, even though it can be seen that 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 PF. 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 the power quality of the grid without the usual bulky and costly series transformer.

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