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Transformer less Series Active Filter for Power Quality Improvement

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Abstract- To upgrade the power quality in single-stage frameworks with critical loads a transformer less hybrid series dynamic channel is proposed . This venture helps the energy administration and power quality issues identified with electric transportation and spotlights on enhancing electric vehicle load association with the grid. The control technique is intended to counteract current harmonic bends of nonlinear loads to stream into the utility and rectifies the power element of this later. While shielding sensitive loads from voltage disturbance influences, droops, and swells started by the power framework, ridded of the arrangement transformer, the design is invaluable for a mechanical usage. This polyvalent half and half topology permitting the symphonious separation and pay of voltage bends could ingest or infuse the assistant energy to the grid. The aggregate consonant bending is decreased with the adequacy of the fluffy controller. This venture additionally examines on the impact of increases and postponements in the continuous controller dependability. The simulation result brought out through MATLAB/SIMULINK programming.

Index Terms— **Current harmonics, electric vehicle, hybrid series active filter (HSeAF), power quality, real-time control, fuzzy controller.**

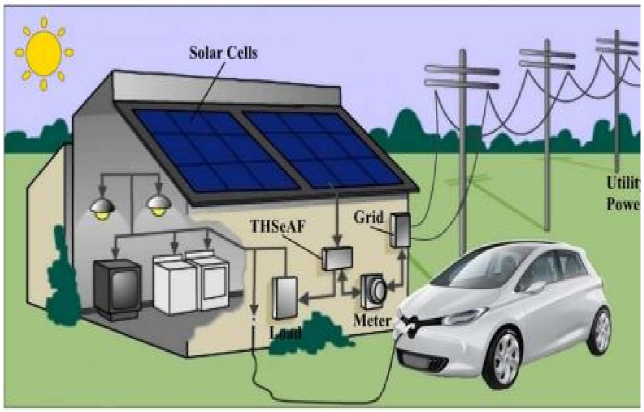
I. INTRODUCTION

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], [3] have detrimental effects on power distribution system harmonic voltage levels [4]. 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 [7], [8]. 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 (HSeAF) 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 project, a single-phase transformer less HSeAF 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 . 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 transformer less hybrid series active filter (THSeAF)[1] 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 . This project 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 the correction of current and voltage distortions, PF correction, and voltage restoration on the load terminal [18]. This project is organized as follows. The system architecture is introduced in the 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..

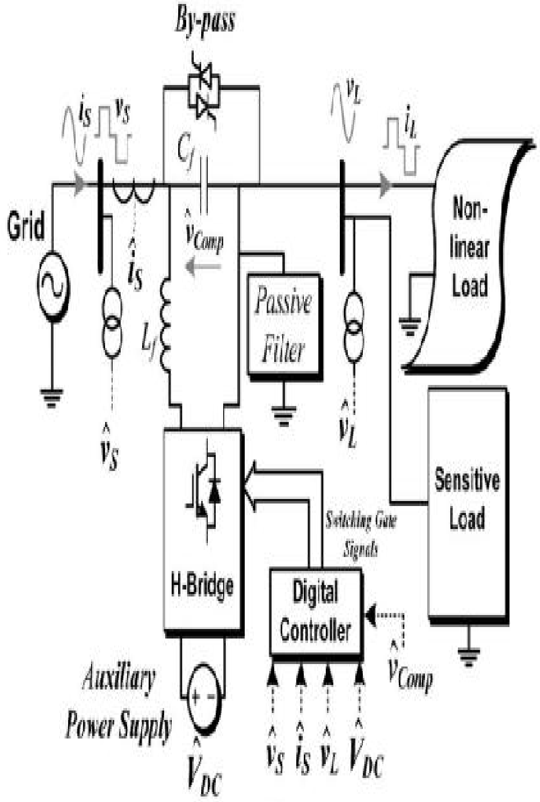
II. SYSTEM ARCHITECTURE

A. System Configuration

The THSeAF appeared in Fig. 1 is made out of a H-connect converter associated in arrangement between the source and the heap. A shunt latent capacitor guarantees a low impedance way for current sounds. A dc assistant source could be associated with infuse control amid voltage droops. The dc-interface energy stockpiling framework is described (19).



(a)



(b)

Fig 1.1. (a) Schematic of a single-phase smart load with the compensator installation. (b) Electrical diagram of the THSeAF in a single-phase utility.

The framework is actualized for an evaluated force of 2200 VA. To guarantee a quick transient reaction with adequate steadiness edges over an extensive variety of operation, the controller is actualized on a dSPACE/dsp1103. The framework parameters are recognized in Table I. A variable wellspring of 120 Vrms is associated with a 1.1-kVA nonlinear load and a 998-VA direct load with a 0.46 PF. The THSeAF is associated in arrangement keeping in mind the end goal to infuse the remunerating voltage. On the dc side of the compensator, a helper dc-connect vitality stockpiling framework is introduced. Comparative parameters are additionally connected for commonsense execution.

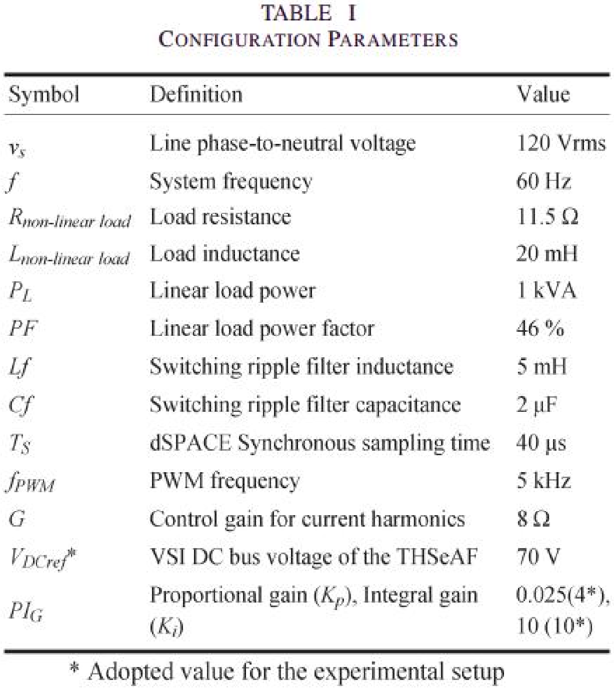


TABLE I
CONFIGURATION PARAMETERS

Symbol	Definition	Value
v_s	Line phase-to-neutral voltage	120 Vrms
f	System frequency	60 Hz
$R_{non\text{-}linear\ load}$	Load resistance	11.5 Ω
$L_{non\text{-}linear\ load}$	Load inductance	20 mH
P_L	Linear load power	1 kVA
PF	Linear load power factor	46 %
Lf	Switching ripple filter inductance	5 mH
Cf	Switching ripple filter capacitance	2 µF
T_S	dSPACE Synchronous sampling time	40 µs
f_{PWM}	PWM frequency	5 kHz
G	Control gain for current harmonics	8 Ω
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

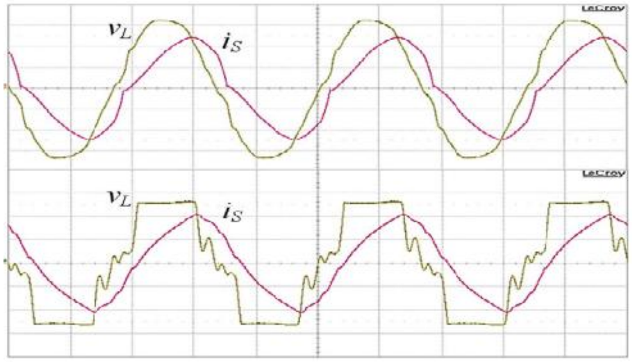


Fig. 1.2. Terminal voltage and current waveforms of the 2-kVA single phase system without compensator. (a) Regular operation. (b) Grid's voltage distortion (scales: 50 V/div for channel 1and 10 A/div for channel 2).

HSeAFs are frequently used to remunerate contortions of the flow sort of nonlinear burdens. For example, the twisted current and voltage waveforms of the nonlinear framework amid ordinary operation and when the source voltage got to be distinctly bended are portrayed in Fig. 2. The THSeAF is skirted, and ebb and flow sounds streamed straightforwardly into the framework. As one can see, notwithstanding amid ordinary operation the present sounds (with an aggregate consonant twisting (THD) of 12%) misshape the PCC, bringing about a voltage THD of 3.2%. The conduct of the framework when the network is profoundly contaminated with 19.2% of THD is likewise shown.

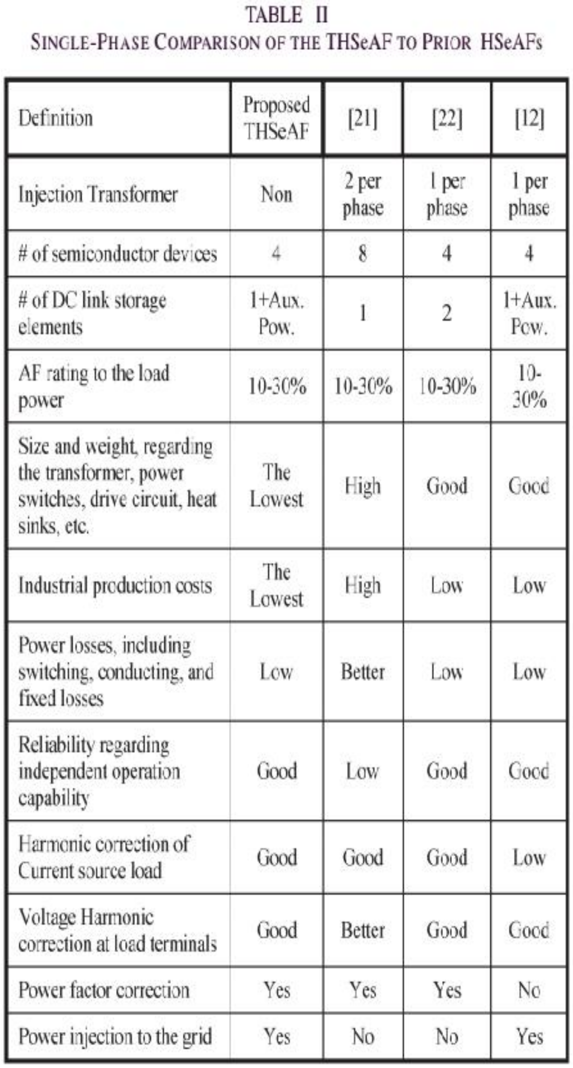


TABLE II
SINGLE-PHASE COMPARISON OF THE THSeAF TO PRIOR HSeAFs

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

. The proposed arrangement could be exclusively associated with the network with no need of a massive and expensive arrangement infusion transformer, making this topology fit for repaying source current sounds and voltage bending at the PCC. Regardless of the possibility that the quantity of switches has expanded, the transformerless design is more financially savvy than some other arrangement compensators, which for the most part uses a transformer to infuse the pay voltage to the power lattice. The streamlined inactive channel is made out of fifth, seventh, and highpass channels. The latent channel ought to be balanced for the framework upon load and government controls. A correlation between various existing setups is given in Table II. It is expected to bring up the preferences and weaknesses of the proposed setup over the traditional topologies. To underscore the correlation table reasonably, the proportionate single period of every design is considered in the assessment. Money related creation assessment exhibited a 45% decrease in segment costs and impressive diminishment in gathering terms too.

OPERATION PRINCIPLE

The SeAF represents a controlled voltage source (VSI). In order to prevent current harmonics i_{Lh} to drift into the source.

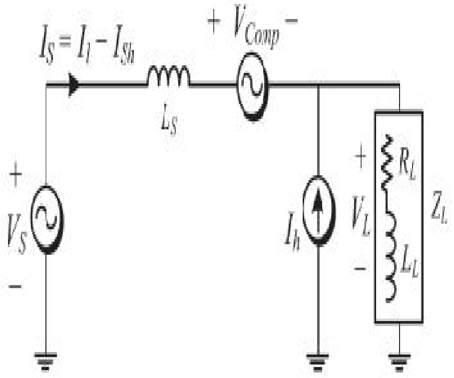


Fig. 1.3. THSeAF equivalent circuit for current harmonics.

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 Z_L represents the nonlinear load and the inductive load. The SeAF 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)

$$V_{comp} = G.I_{sh} - V_{Lh}. \qquad (1)$$

This allows having individual equivalent circuit for the fundamental and harmonics

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

The source harmonic current could be evaluated

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

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

Combining (3) and (4) leads to

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

If gain G is sufficiently large (G → ∞), the source current will become clean of any harmonics(Ish → 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

Average and Small-Signal Modeling

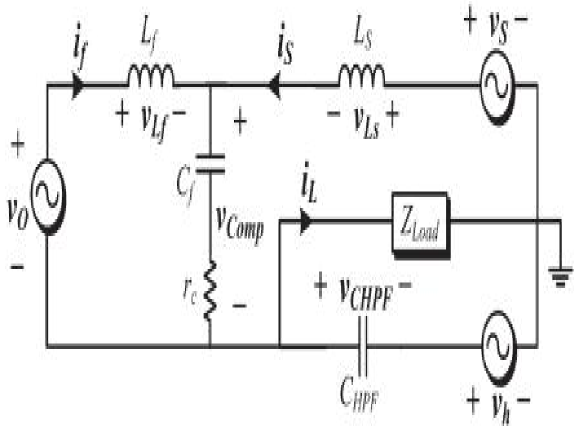


Fig. 2.1. Small-signal model of transformer less HSeAF in series between the grid and the load.

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. Here after, *d* is the duty cycle of the upper switch during a switching period, whereas $\bar{v}$and $\bar{\imath}$ 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.

$$\bar{v}_O = \underbrace{(2d-1)}V_{\mathrm{DC}} \qquad (6)$$

where the (2d−1) equals tom, then

$$\bar{\imath}_{\mathrm{DC}} = m\bar{\imath}_f. \qquad (7)$$

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

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

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:

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

Hence, we obtain

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

Moreover, the output vector is

$$y = Cx + Du \qquad (11$$

Or

$$\begin{bmatrix} \bar{v}_{\mathrm{comp}} \\ \bar{v}_L \end{bmatrix} = \begin{bmatrix} 1 & 0 & r_c & r_c & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix} \times \begin{bmatrix} \bar{v}_{Cf} \\ \bar{v}_{CHPF} \\ \bar{i}_S \\ \bar{i}_f \\ \bar{i}_L \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} \times \begin{bmatrix} \bar{v}_S \\ V_{\mathrm{DC}} \\ \bar{v}_h \end{bmatrix}. \qquad (1$$

By means of (10) and (12), the state-space representation of the model is obtained as shown in Fig. 2.1.

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.

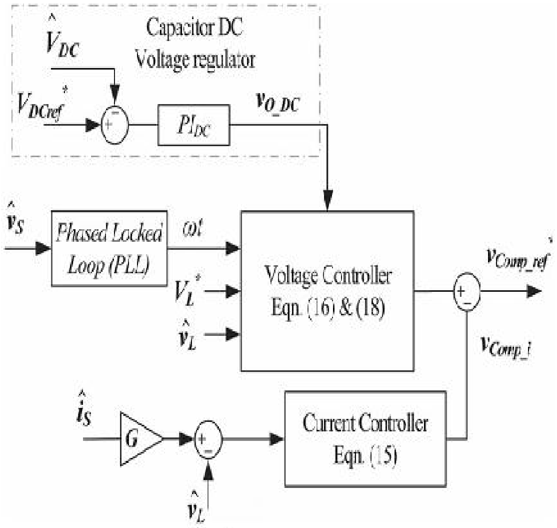


Fig. 2.2. Control system scheme of the active part**.**

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

$$T_V(s) = \frac{V_{\mathrm{comp}}}{V_O} = \frac{r_C C_f s + 1}{L_f C_f s^2 + r_C C_f s + 1} \qquad (13)$$

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

The further detailed derivation of steady-state transfer functions is described in 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. 2.2.

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. 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 equ(15)

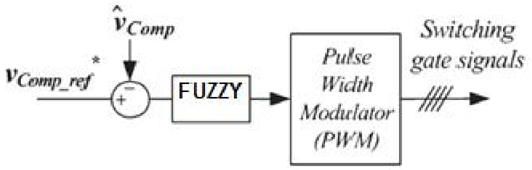


FIG2.3 Block diagram of THSeAF and Fuzzy controller

$$v_{\text{comp\_i}}(t) = \left(-G\hat{i}_S + \hat{v}_L\right) - \left[\,-Gi_{S1} + v_{L1}\right] \cdot \sin(\omega_S t - \theta).$$
(15)

Stability analysis of voltage and current harmonics was explained in (1)

IV.Simulation Block Diagram and Results

The proposed transformerless-HSeAF configuration was simulated in MATLAB/Simulink using discrete time steps of $Ts = 10\ \mu$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 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 ***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 THSeAF 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. Experimental results obtained in the laboratory corroborate the successful operation of the THSeAF shown in simulations. The compensator during steady state operating with parameters described in Table I. The source current became sinusoidal, and the load voltage was regulated at rated 120 Vrms. The source current is in phase with the utility voltage, achieving a unity PF correction.

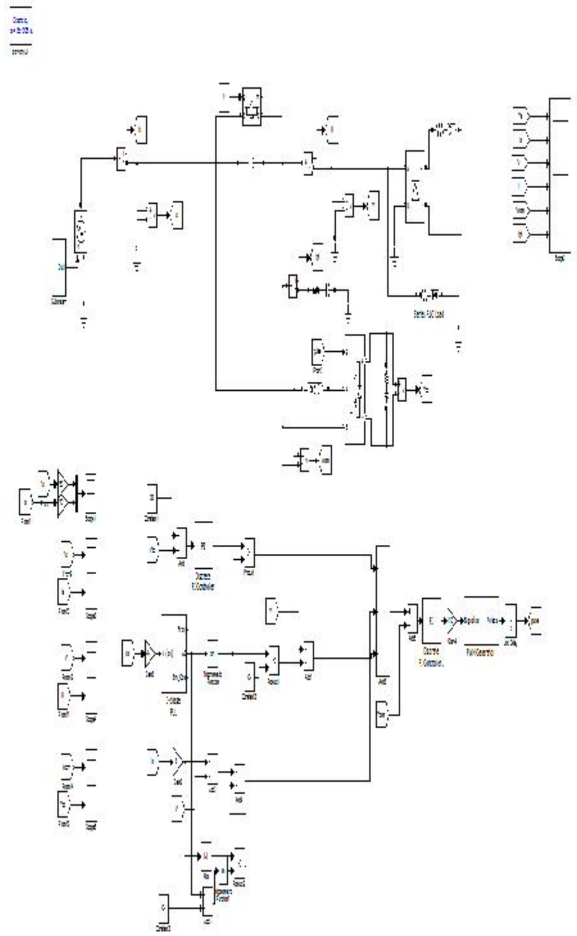


Fig3.1Simulation block diagram of THSeAF

OUT PUT WAVE FORMS:

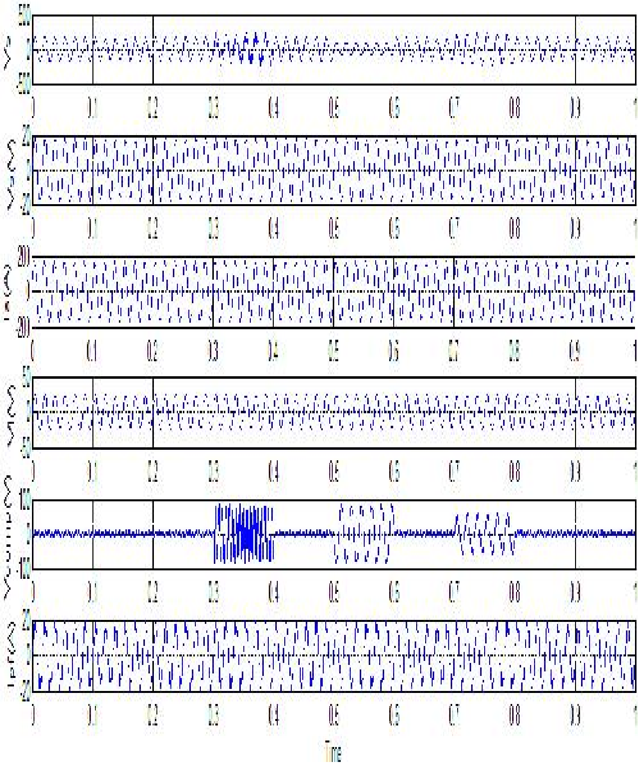
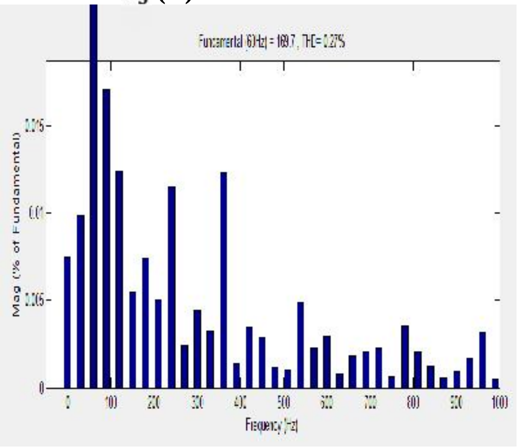


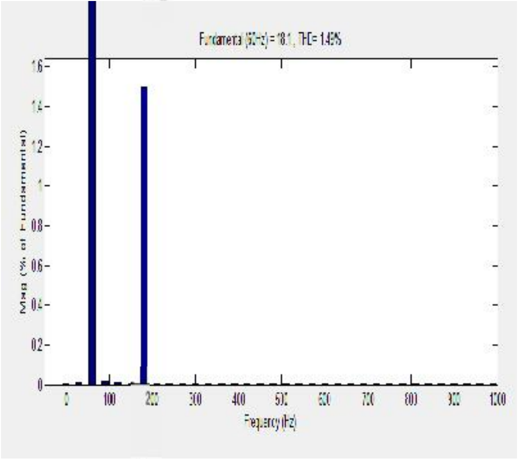
Figure 3.2 Simulation of the system with the THSeAF and Fuzzy logic controller compensating current harmonics and voltage regulation. (a) Source voltageV_s, (b) source currenti_s, (c) load voltage V_L, (d) load current i_l, (e) active-filter voltage V_{comp}, and (f) harmonics current of the passive filter i_{PF} .

6.9 Total Harmonic Distortion Using With Fuzzy Controller:

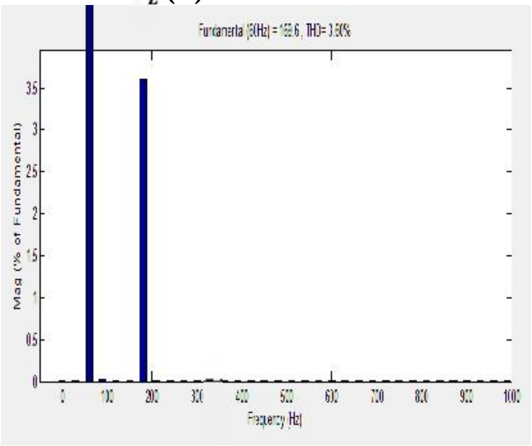
V_S (V) THD=0.27%



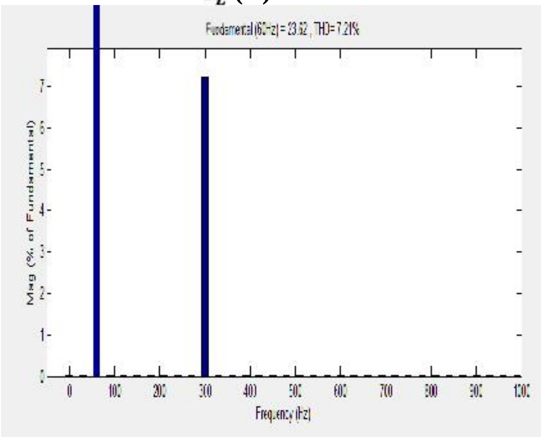
I_S (V) THD=1.49%



V_L (V) THD=3.60%



I_L (V) THD=7.21%



CONCLUSION

In this project, a transformer less HSeAF for power quality improvement was developed and tested. The project 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. Fuzzy controller is implemented in this project to reduce the harmonic distortion of load current. The proposed transformer less configuration was simulated. 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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