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Power Quality Improvement by Hybrid Series Single Phase Active Filter without transformer

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Abstract:
This paper helps energy management and power quality issues identified with electric transportation and concentrates on enhancing electric vehicle load association with the grid. A transformerless hybrid series active channel is proposed to upgrade the power quality in single-phase systems with critical loads. The control strategy is de-marked to avoid current harmonic mutilations of nonlinear loads to stream into the utility and rectifies the power factor of this later. While shielding delicate loads from voltage disturbances, sags, and swells started by the power sys-tem, ridded of the series transformer, the setup is invaluable for a modern industrial execution. This hybrid topology permitting the harmonic isolation and compensation of voltage distortions could assimilate or infuse the auxiliary power to the grid.

Keywords — **Current harmonics, electric vehicle, hybrid series active filter (HSeAF), power quality, real-time control**

I. INTRODUCTION

The estimate of future Smart Grids related with electric vehicle charging stations has made a genuine worry on all parts of energy nature of the power system, while across the board electric vehicle battery charging units [1], [2] effectsly affect control dispersion system consonant volt-age levels [3]. Then again, the development of music bolstered from nonlinear burdens like electric vehicle propulsion battery chargers [4], [5], which in fact impactsly affect the power system and influence plant hardware, ought to be considered in the improvement of current grids. Similarly, the expanded rms and pinnacle estimation of the distorted current waveforms increment warming and misfortunes and cause the disappointment of the electrical gear. Such marvel successfully diminishes system effectiveness and ought to have legitimately been tended to. Also, to secure the point of common coupling (PCC) from voltage mutilations, utilizing a dynamic voltage restorer (DVR) work is prompted. An answer is to diminish the pollution of energy hardware based loads specifically at their source. Albeit a few endeavors are made for a particular contextual investigation, a bland arrangement is to be investigated. There exist two types of active power gadgets to defeat the depicted power quality issues. The primary category are series active filters (SeAFs), including hybrid-type ones. They were created to dispose of current harmonics delivered by nonlinear load from the power system. SeAFs are less scattered than the shunt type of active filters [8], [9]. The benefit of the SeAF contrasted with the shunt type is the second rate rating of the compensator versus the load nominal rating [10]. Notwithstanding, the multifaceted nature of the setup and need of a detachment series transformer had decelerated their mechanical application in the appropriation system. The second category was produced nature of the setup and need of a detachment series transformer had decelerated their mechanical application in the appropriation system. The second category was produced in worry of tending to voltage issues on sensitive loads. Commonly known as DVR, they have a comparative design as the SeAF. These two classifications are not quite the same as each other in their control rule. This distinction depends on the reason for their application in the system.

The hybrid series active filter (HSeAF) was proposed to address the previously mentioned issues with just a single blend. Hypothetically, they are competent to remunerate current harmonics, guaranteeing a power factor (PF) revision and dispensing with voltage twists at the PCC [9]. In this paper, a single-phase transformerless HSeAF is proposed and capable of cleaning up the grid-side connection bus bar from current harmonics generated by a nonlinear load. With a littler rating up to 10%, it could without much of a stretch supplant the shunt active filter [8]. Furthermore, it could re-establish a sinusoidal voltage at the load PCC.

The benefit of the proposed arrangement is that non-direct consonant voltage and current creating loads could be adequately adjusted. The transformerless hybrid series active filter (THSeAF) is an elective alternative to regular power transferring converters in conveyed age systems with high entrance of sustainable power sources, where each phase can be controlled independently and could be worked autonomously of other phases [7]. This paper demonstrates that the detachment of a three-phase converter into single-phase H-connect converters has permitted the end of the expensive disengagement transformer and advances modern application for filtering purposes. The setup has indicated awesome capacity to perform asked for remunerating assignments for the correction of current and voltage distortions, PF correction, and voltage restoration on the load terminal.

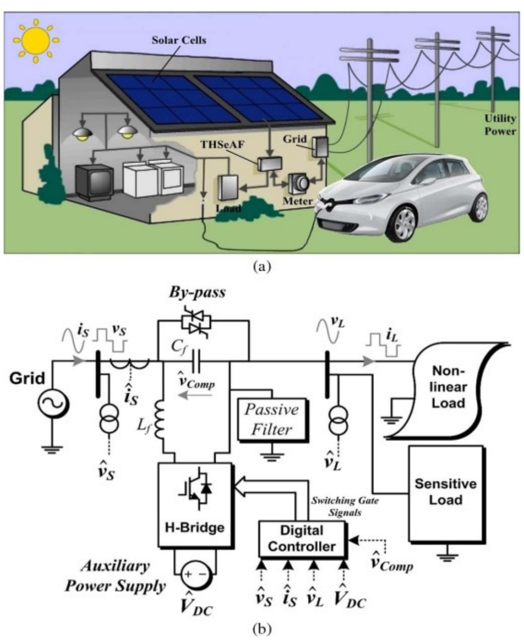


Fig. 1. (a) Schematic of a single-phase smart load with the compensator installation. (b) Electrical diagram of the THSeAF in a single-phase utility.

This paper is sorted out as follows. The system design is presented in the accompanying segment. Then, the operation rule of the proposed arrangement is clarified. The third area is committed to the displaying and examination of the control calculation actualized in this work. The dc voltage control and its contemplations are quickly clarified, and the voltage and current symphonious recognition strategy is expressly depicted. To assess the setup and the control approach, a few situations are mimicked. This paper is outlined with a conclusion and supplement where further mathematical improvements are illustrated.

II SYSTEM ARCHITECTURE

A. System Configuration

The THSeAF shown in Fig. 1 is made out of a H-bridge converter connected in series between the source and the load. A shunt uninvolved capacitor guarantees 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 depicted in [9]. The system is executed for an appraised energy of 2200 VA. The system parameters are distinguished in Table I. A variable source of 120 V_{rms} is connected to a 1.1-kVA nonlinear load and a 998-VA straight load with a 0.46 PF. The THSeAF is connected in series with a specific end goal to infuse the repaying voltage. On the dc side of the compensator, an auxiliary dc-link energy storage system is introduced. Comparative parameters are likewise connected for handy usage.

HSeAFs are frequently used to remunerate distortions of the current sort of nonlinear loads. For example, the contorted current and voltage waveforms of the nonlinear system amid ordinary operation and when the source voltage progressed toward becoming dis-torted are delineated in Fig. 2. The THSeAF is circumvent, and current harmonics flowed directly into the grid. As one can

TABLE I
CONFIGURATION PARAMETERS

Symbol	Definition	Value
v_s	Line phase-to-neutral voltage	120 Vrms
f	System frequency	50 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

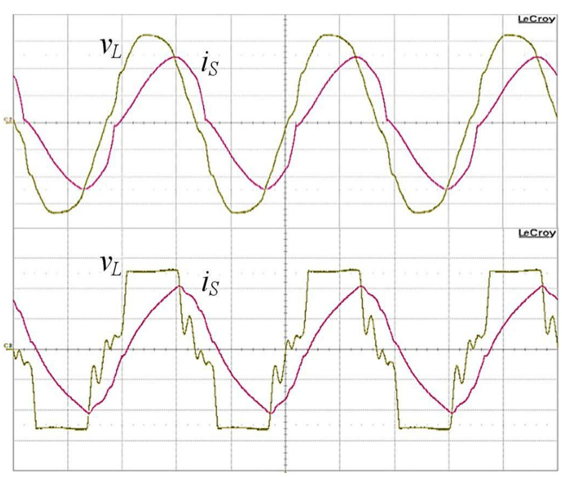


Fig. 2. Terminal voltage and current waveforms of the 2-kVA single-phase system without compensator. (a) Regular operation. (b) Grid's voltage distortion (scales: 50 V/div for channel 1 and 10 A/div for channel 2).

See, even amid normal operation, the current harmonics (with a total harmonic distortion (THD) of 12%) distort the PCC, bringing about a voltage THD of 3.2%. The behavior of the system when the grid is highly contaminated with 19.2% of THD is also illustrated. The proposed configuration could be exclusively 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 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 made out of 5th, 7th, and 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 call attention to the advantages and disadvantages of the proposed configuration over the conventional topologies.

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

To emphasize the comparison table fairly, the equivalent single phase of each configuration is considered in the evaluation 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.

B. Operation Principle

The SeAF represents a controlled voltage source (VSI). In or-der 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].

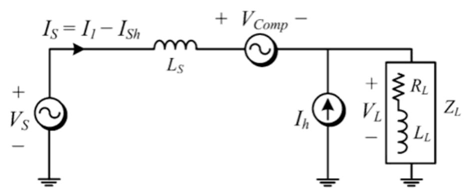


Fig. 3. THSeAF equivalent circuit for current harmonics.

The utilization of an tuned passive filter is then mandatory to play out the compensation of current issues and maintaining a constant voltage free of distortions at the load terminals. The behaviour 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 displayed by a resistance speaking to the active power devoured and a current source generating current harmonics. Accordingly, the impedance ZL speaks to 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 har-monics (I_{sh}) flowing to the grid (V_s)

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

This allows having individual equivalent circuit for the fundamental and harmonics

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

The source harmonic current could be evaluated

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

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

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

$$I_{sh}=V_{sh} /(G-Z_S) \quad (5)$$

If that gain G is adequately substantial (G → ∞), the source current will turn out to be spotless of any harmonics (Ish → 0). This will help enhance the voltage distortion at the grid side. In this approach, the THSeAF acts as high-impedance open circuit for current harmonics, while the shunt high-pass filter tuned at the system frequency makes a low-impedance way for all harmonics and open circuit for the central; it additionally 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 [3],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 v^{-} and ^{-}i denote the average values in a switching period of the voltage and current of the same leg.

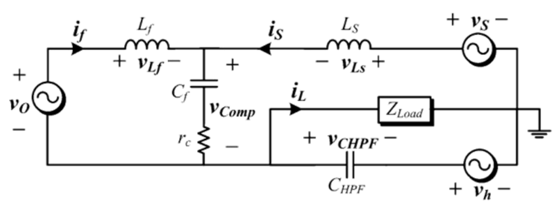


Fig. 4. Small-signal model of transformerless

HSeAF in series between the grid and the load. The mean converter output voltage and current are expressed by (6) and (7) as follows:

$$v^{-}{}_O = (2d - 1)V_{DC} \quad (6)$$

where the $(2d - 1)$ equals to m, then

$$i^{-}{}_{DC} = m \, i^{-} f \quad (7)$$

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

$$v^{-} h(j\omega) = -j^{-} ih \ CHP \ F \cdot \omega h . \quad (8)$$

On the off chance that the harmonic frequency is sufficiently high, it is conceivable to accept that there will be no voltage harmonics across the heap. The state-space small-signal ac model could be determined by a linearized perturbation of the averaged model as takes after:

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

Hence, we obtain:

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

Moreover, the output vector is

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

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

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

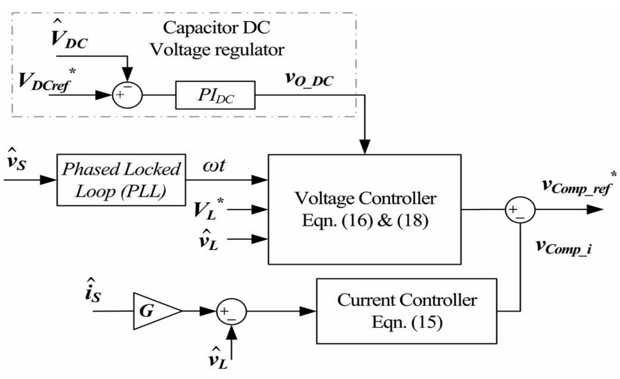


Fig. 5. Control system scheme of the active part.

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.

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

$$T_{V\,m}(s) = V_{comp}/m = V_{DC} \cdot T_V(s) \quad (14)$$

The further point by point derivation of steady-state transfer functions is depicted in Section V. A dc assistant source ought to be utilized to keep up a satisfactory supply on the heap terminals. Amid the sag or swell conditions, it ought to ingest or inject energy to keep the voltage magnitude at the heap terminals inside a predefined edge. Be that as it may, if the compensation of sags and swells is less goal, a capacitor could be conveyed. Subsequently, the dc-link voltage over the capacitor ought to be managed as shown in Fig. 5

B. Voltage and Current Harmonic Detection

The outer-loop controller is utilized where a capacitor replaces the dc auxiliary source. This control strategy is very much clarified in the past area. The inner-loop control strategy is based on an aberrant control guideline. A fast Fourier transformation was utilized to separate the extent of the basic and its phase degree from current harmonics. The control gain G to the impedance of the source for current harmonics has an adequate level to clean the grid from current harmonics encouraged through the nonlinear load. The second proportional integrator (PI) controller utilized as a part of the outer loop was to improve the viability of the controller when managing the dc bus Consequently, a more precise and faster transient response was accomplished without compromising the compensation behavior of the system. As per the hypothesis, the gain G ought to be kept in a reasonable level, keeping the harmonics from streaming into the grid [2]. As beforehand talked about, for a more exact remuneration of current harmonics, the voltage harmonics ought to likewise be considered. The compensating voltage for current consonant remuneration is gotten from

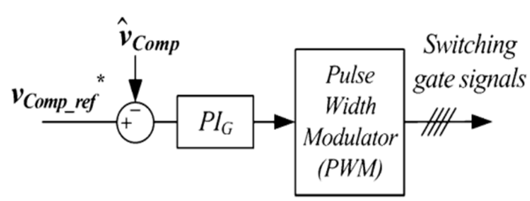


Fig. 6. Block diagram of THSeAF and PI controller.

Therefore, as voltage distortion at the load terminals isn't wanted, the voltage sag and swell ought to likewise be examined in the inner loop. The closed-loop equation (16) permits to by implication keep up the voltage magnitude at the load side equivalent to V^{*}_{L} as a predefined esteem, inside satisfactory margins.

$$v_{comp\_v} = \hat{v}_L - V_L^{*} \sin(\omega_S\, t). \qquad (16)$$

The whole control conspire for the THSeAF displayed in Fig. 5 was utilized and executed in MATLAB/Simulink for real-time simulations and the figuring of the compensating voltage.. The source and load voltages, together with the source current, are considered as system input signals. As indicated by Srianthumron. [2,5], a circuitous control expands the stability of the system.

The source current harmonics are gotten by removing the fundamental component from the source current.

$$v^{*}_{com\_ref} = v_{comp\_v} - v_{comp\_i} + v_{DC\_ref} \qquad (17)$$

where the v_{DC_ref} is the voltage required to maintain the dc bus voltage constant.

$$v_{DC\_ref}\,(t) = V_{O\_DC} \cdot \sin(\omega_S\, t). \qquad (18)$$

A phase-locked loop was utilized to acquire the reference angular frequency (ωs). In like manner, the separated current symphonious contains a fundamental component synchronized with the source voltage keeping in mind the end goal to redress the PF. This current represent to the reactive power of the load. The gain G representing to the protection for harmonics changes over current into a relative voltage. The created reference voltage v_{comp_i} required to clean the source current from harmonics is depicted in (15).

As per the introduced recognition algorithm, the compensated reference voltage $v*_{Com\_ref}$ is figured. From there on, the reference signal is contrasted and the measured output voltage and connected to a PI controller to produce the comparing gate signals as in Fig. 6.

C. Stability Analysis for Voltage and Current Harmonics

The stability of the configuration is for the most part influenced by the presented delay of a digital controller. This area contemplates the effect of the delay first on the inclusive compensated system as per works refered to in the writing. From there on, its consequences for the active compensator is isolated from the grid. Utilizing simply inductive source impedance (see Fig. 4) and Kirchhoff's law for harmonic frequency components, (19) is inferred. The delay time of the digital controller, huge gain G, and the high solidness of the system truly influence the stability of the closed-loop controlled system.

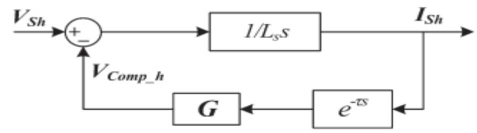


Fig. 7. Control diagram of the system with delay

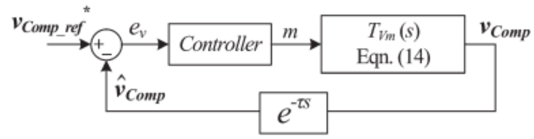
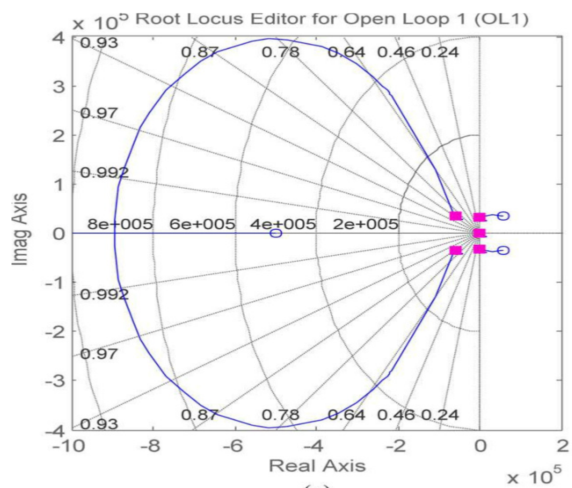


Fig. 8. Closed-loop control diagram of the active filter with a constant delay time τ

$$I_{sh}(s) = (V_{sh} - V_{comp} - V_{Lh}) / L_s S \qquad (19)$$

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

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



(a)

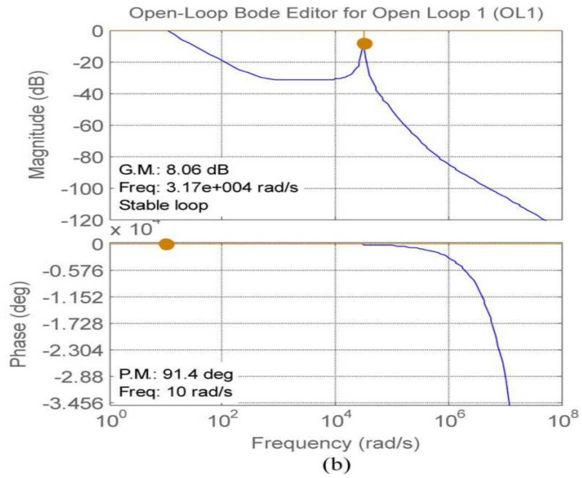


Fig. 9. Compensated open-loop system with delay time of 40 *μs*. (a) Root locus diagram. (b) Bode diagram

Considering (19) and (20), the control diagram of the system with delay is obtained as in Fig. 7.The overall delay of the system is assumed to be a constant value τ . Therefore, the open-loop transfer function is obtained

$$G(S) = (G/L_s S)\, e^{\tau s} \qquad (21)$$

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

$$G < (\pi L_s)/2\tau \qquad (22)$$

A system with a regular source inductance Ls of 250 μH and a delay of 40 μs is viewed as steady as indicated by (22) when the gain G is littler than 10ω. . Besides, the impact of the delay on the control calculation ought to likewise be researched. As per the transfer functions (13) and (14), the control of the active part is influenced by the delay present by the digital controller. Along these lines, accepting an ideal switching characteristic for the IGBTs, the closed-loop system for the active part controller is appeared in Fig. 8.

The open-loop transfer work in Fig. 8 swings to , where the τ is the delay time started by the digital controller

A P I controller with system parameters portrayed in Table I exhibits a smooth operation in the steady locale. By meansof MATLAB, the conduct of the system's transfer work F(s) is followed in Fig. 9. The root locus and the Bode outline of the compensated open-loop system show a gain edge of 8.06 dB and a stage edge of 91◦. Moreover, for an additional hypothetical examination, the impact of the delay on the heap voltage could likewise be assessed concerning the transfer work TV _LS (s) depicted in the Appendix..

IV. SIMULATIONS RESULTS

The proposed transformerless HSeAF configuration was mimicked in MATLAB/Simulink utilizing discrete time ventures of T s = 10 μsTo guarantee a error-free and fast implementation, the total control loop was executed each 40 μs. The parameters are recognized in Table I.The mix of a solitary phase nonlinear load and a linear load with a total rated power of 2 kVA with a 0.74 slacking PF is connected for research facility investigations and reproductions. For analyses and reenactments, a 2-kVA 120-Vrms 50-Hz variable source is utilized. THSeAF associated in series to the system remunerates the current harmonics and voltage distortions. The complete experimental system is demonstrated in Fig. 10

A gain G = 8 Ω proportional to 1.9 p.u. was utilized to control current harmonics. As specified before, the capacity of operation with low dc

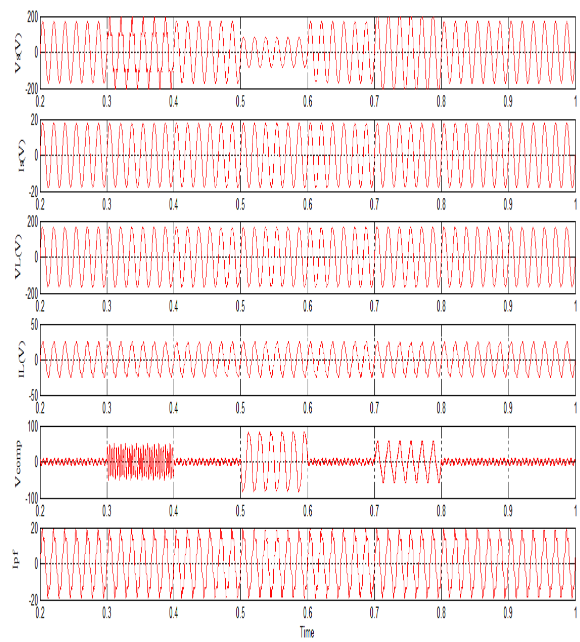


Fig. 11. Simulation of the system with the THSeAF compensating current harmonics and voltage regulation. (a) Source voltage V_S, (b) source current I_S, (c) load voltage V_L, (d) load current I_L, (e) active-filter voltage V_{Comp}, and (f) harmonics current of the passive filter I_{PF}.

voltage is considered as one of the principle favorable circumstances of the proposed configuration. . Amid a grid's voltage distortion, the compensator controls the load voltage extent, repays current harmonics, and amends the PF. The recreated after effects of the THSeAF illustrated in Fig. 11 illustrates change in the source current THD. The load terminal voltage VL THD is 4.3%, while the source voltage is very contorted (THD VS = 25%).

The grid is cleaned of current harmonics with a solidarity power factor (UPF) operation, and the THD is decreased to not exactly 1% in typical operation and under 4% amid grid annoyance. While the series controlled source cleans the current of harmonic components, the source current is compelled to be in phase with the source voltage. The series compensator has the capacity to slide the load voltage all together for the PF to achieve solidarity. Moreover, the series compensator could control the power flow between two PCCs.

V. SUMMARY

In this paper, a transformerless HSeAF for power quality change was produced. The paper featured the way that, with the ever increment of nonlinear loads and higher exigency of the consumer for a dependable supply, solid moves ought to be made into thought for future smart grids keeping in mind the end goal to easily coordinate electric car battery chargers to the grid. The key curiosity of the proposed arrangement is that the proposed configuration could enhance the power quality of the system in a more broad manner by remunerating an extensive variety of harmonics current, despite the fact that it can be seen that the THSeAF controls and enhances the PCC voltage.

Associated with a renewable auxiliary source, the topology can neutralize actively to the power stream in the system. This basic capacity is required to guarantee a reliable supply for basic loads. Acting as high-harmonic impedance, it cleans the power system and guarantees a unity PF. The hypothetical demonstrating of the proposed configuration was examined. The proposed transformerless configuration was recreated and tentatively approved. It was demonstrated that this active compensator reacts appropriately to source voltage varieties by giving a steady and distortion-free supply at load terminals. Moreover, it disposes of source harmonic currents and enhances the power quality of the grid without the typical cumbersome and expensive series transforme

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