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Power Quality Enhancement of Smart Households using a Multilevel THSeAF with a PR Controller

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***Abstract* — In this paper a Multilevel TransformerlessHybrid Series Active Filter (Multilevel-THSeAF) is proposed to enhance the power quality of a single-phase residential household. The proposed topology reflects new trends of consumers towards electronic polluting loads and integration of renewable sources which in fact may lead to the scope of a reliable and sustainable supply. This paper contributes to improvement of power quality for a modern single-phase system and emphasis integration of a compensator with energy storage capacity to ensure a sustainable supply. A proportional resonant (P+R) regulator is implemented in the controller to prevent current harmonic distortions of various non-linear loads to flow into the utility. The main significant features of the proposed topology include the great capability to correct the power factor as well as cleaning the grid simultaneously, while protecting consumers from voltage disturbances, sags, and swells during a grid perturbation. It investigates aspects of harmonic compensation and assesses the influence of the controller's choice and time delay during a real-time implementation. Combinations of analysis and experimental results performed on a laboratory setup are presented for validation.**

***Index Terms* –Hybrid active filters, power quality, renewableenergysources, multilevel converters, smart grids, real-time control, resonant controller, nonlinear loads.**

I. INTRODUCTION

THE trends toward a future Smart Grid implementation and the ever increase of numerous nonlinear industrial, commercial and residential type of loads that are generating pollution which led to 100% of total current harmonic distortions into the grids have drastically created a concern on power quality metrics for future power systems [1]. The increase in electronics devices as shown in Fig. 1, associated with fast charging [2, 3] devices with external energy sources require early investigation on harmonic and non-active power compensation [4]. This widespread harmonic polluting device not only reduce the system's efficiency, but also has detrimental impacts on grid voltage distortion levels [5]. Likewise, distorted current waveform creates additional heating losses, and causes failure in sensitive electrical devices. Several references could be found in the literature addressing specified [6, 7] or common cases dealt with power quality issues either related to voltage distortions or current harmonics [8].

This paper addresses the new research challenges that are facing the power electronics converters to participate actively in mitigating electric types of pollution and consequently enhance the grid so as to supply clean and reliable energy to the fast-growing energy demand [9] by highly nonlinear and time varying loads. The efficient and affordable solution proposed in this paper uses a multilevel configuration [10] to reduce dc side voltage for low level distribution system as demonstrated in Fig. 2. The use of this device will facilitate the integration of energy storage systems and renewables for modern households [11, 12]. It is noteworthy to mention that this proposed configuration does not necessitate the bulky series transformers [13] which constitute an economic key toward cost effective power quality improvement of future grids.

This multifunctional compensator cleans the current drawn from the utility and similarly to a Dynamic voltage restorer (DVR) the point of common coupling (PCC) and

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utility smart meters will be protected from voltage distortions so as to avoid wrong computation of power and energy balance. This compensator could inject or absorb active power during grid voltage variations to ensure high quality supply along with complete decoupling from polluted loads.

The increase of charging stations [14] in a residential neighborhood and commercial buildings becomes crucial to monitor and evaluates their power quality characteristics [15]. In addition, pushed by social efforts, distributed generation and renewable energy sources are been popularized requiring more research and investigation on their wide application on the power quality of the system [16]. This work proposes an efficient Transformerless Hybrid Series Active Filter (THSeAF) capable of rectifying current related issues in such micro-grid application and provides sustainable and reliable voltage supply at the PCC where important residential consumers are connected.

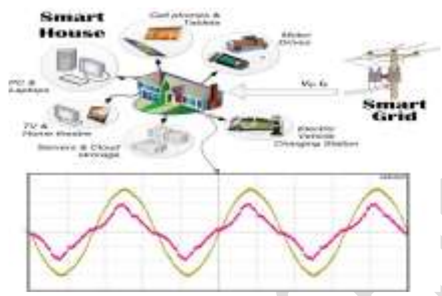


Fig. 1. Typical modern residential consumer with non-linear electronic loads and a Nissan LEAF® measured voltage and current waveforms plugged to a level-2 charging station.

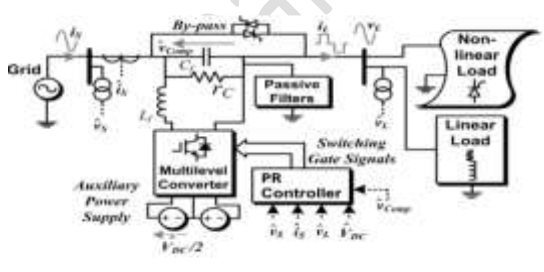


Fig. 2. House equivalent circuit connection with utility meters and the Multilevel-THSeAF connected in series.

This paper is organized as follows; the system configuration will be first introduced. Then the operation principle of the proposed configuration is explained. The third section will be dedicated to the modeling and analysis of the control algorithm. The voltage and current harmonic detection method is explicitly described. To evaluate the proposed topology and control behavior, several scenarios are simulated and experimental validations will be presented and discussed.

II. SYSTEM ARCHITECTURE

A. *System configuration*

The compensator depicted in Fig. 2 is composed of a multilevel single-phase converter connected in series between the utility and the house's entrance connected terminals. The transformerless hybrid series active filter is composed of a five-level NPC converter [17] depicted in Fig. 3, connected in series between the utility and the entrance of the building. An auxiliary supply is connected on the dc side. To filter high frequency switching harmonics, a passive filter is used at the output of the converter. A bank of tuned passive filters ensures a low impedance path for current harmonics. In this paper the studied system is implemented for a rated power of 1 kVA. To ensure a fast transient response with sufficient stability margins over a wide range of dynamic operations, the controller is implemented on an Opal-RT/Wanda real-time simulator. For an accurate real-time measurement of electrical variables, the Opal-RT OP8665 probes are performing the measurement task. The system parameters are identified in Table I. A variable source up to 120 Vrms is connected to a 1 kVA non-linear load. 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 simulations. A fast electric vehicle charging plug level-2 is as well connected to the load's PCC. The active compensator's NPC converter structure is depicted in Fig. 3.

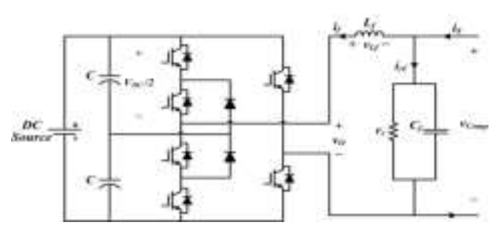


Fig. 3. Hybrid converter topology for the proposed series compensator.

On the DC side of the compensator, auxiliary dc-link energy storage components are installed at a reduced voltage level of 100V. The objective is to propose an efficient device capable of rectifying current related issues in smart grids which also provide sustainable and reliable voltage supply at the point of common coupling that define the entrance of residential or commercial buildings.

TABLE I

CONFIGURATION PARAMETERS

Symbol	Definition	Value
V_S	Line phase-to-neutral voltage	110 Vrms
f	System frequency	60 Hz
L_s	Supply equivalent inductance	150 μH*
R, L	Non-linear CSC load	25 Ω, 20mH
Lf	Switching ripple filter inductance	2.5 mH
Cf	Switching ripple filter capacitance	2 μF
r_C	Switching ripple damping resistor	60 Ω
T_S	Opal-RT Synchronous sampling time	40 μs
f_{PWM}	PWM frequency	8 kHz
F_5	Fifth order shunt passive filter	56μF, 5mH
F_7	Seventh order passive filter	14μF, 10mH
F_{11}	Eleventh order passive filter	6μF, 10mH
F_{HPF}	High-pass filter	2μF
K_p, K_r	Controller proportional and resonant gains	2.5, 10
ω_C	Cutoff frequency	5 rad/s
V_{DC}	dc auxiliary power supply voltage	110 V, 120 V*

* Adopted value for the simulation analysis

Using the circuit of Fig. 2 showing the block diagram and model of equivalent house circuit connection with utility meters and Multilevel-THSeAF connected in series, several critical scenarios such as grid distortion, sag or swell are simulated using discrete time steps of 40μs. The Multilevel-THSeAF connected in series injects a compensating voltage which results in a drastic improvement of source current distortions and a cleaned load voltage. While the load current contains a THDI_L of 12%, the source current is cleaned with a THDI_S of 2.1%. When the utility is highly polluted with a THDV_S of 25.5%, the load voltage is regulated and contains a THD of only 1.2%.

B. Operation principle

A current fed type of non-linear load could be modeled as a harmonic voltage source in series with an impedance $Z_{Non\text{-}Linear}$ or by its Norton equivalent modeled with a harmonic current source in parallel to the impedance. Thévenin's model and Norton's equivalent circuit are depicted in Fig. 4. In this paper the common Norton's equivalent is chosen to follow major related papers. In this work the approach to achieve optimal behavior during the time the grid is perturbed is implemented on the controller [18]. The use of a passive filter is mandatory to compensate current issues and maintaining a constant voltage free of distortions at the load terminals. The non-linear load is modeled by a resistance representing the active power consumed and a current source generating harmonic current. Accordingly, the impedance Z_L is the equivalent of the nonlinear ($Z_{Non\text{-}linear}$) and the linear load (Z_{RL}). The Series active filter, whose output voltage V_{comp} is considered as an ideal controlled voltage source is generating a voltage based on the detecting source current, load voltage, and also the source voltage to achieve optimal results as of (4). This established hybrid approach gives good result and is quite less sensitive to the value of the gain $\boldsymbol{G}$ to achieve low levels of current harmonics. The gain $\boldsymbol{G}$ is proportional to the current harmonics (I_{sh}) flowing to the grid. Assuming a non-ideal grid supplying feeder voltage that contains important numbers of voltage distortions (V_{Sh}), the equivalent circuit for the fundamental and harmonics are:

$$V_S=V_{S1}+V_{sh} \text{-----}(1)$$

$$V_L=V_{L1}+V_{Lh}=Z_L I_Z=Z_L(I_S-I_h)(2)$$

$$I_S=I_{S1}+I_{Sh}=I_Z+I_h \quad (3)$$

$$V_{comp}=+GI_{sh}-V_{Lh}+V_{sh}(4)$$

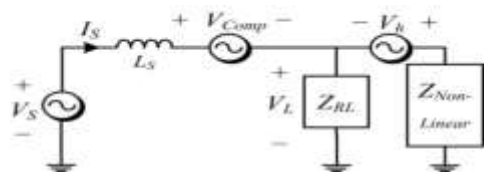
Where IZ represents the load current in ZL shown in Fig. 6. Using the Kirchhoff's law the following equation is depicted for both the fundamental and harmonics.

$$V_S=Z_S I_S+v_{Comp}+v_L(5)$$

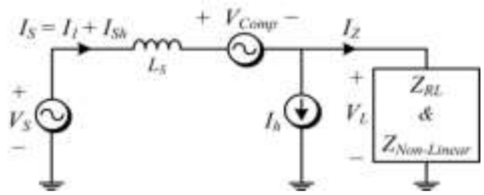
$$V_S=Z_L I_{S1}, \qquad V_{Lh}=z_L(I_{Sh}-I_h)(6)$$

By substituting the fundamental of (6) in (5), the source current at fundamental frequency is obtained.

$$I_{S1}=\frac{V_{S1}}{Z_S+Z_L}(7)$$



(a)



(b)

Fig. 4.Single-phase equivalent phasor model for VSC type of loads, (a) Thévenin's model, (b) Norton equivalent.

By substituting (4) in (5) for the harmonic components, the harmonic source current is reached as follow.

$$V_{Sh}=Z_S I_{Sh}+G I_{Sh}-V_{Lh}+V_{Sh}+V_{Lh} \rightarrow I_{Sh}=0 \qquad (8)$$

By introducing (8) into the harmonic component of the load PCC voltage (6), following equation is achieved.

$$V_{Lh}=-Z_L I_h \qquad (9)$$

Consequently in this approach even in presence of source voltage distortions the source current is always clean of any harmonic component. To some extent in this approach the filter behaves as high impedance likewise an open circuit for current harmonics, while the shunt high pass filter tuned at the system frequency, could create a low-impedance path for all harmonics and open circuit for the fundamental component. This argument explains the need of a Hybrid configuration to create an alternative path for current harmonics fed from a current source type of nonlinear loads.

III. MODELING AND CONTROL OF THE SINGLE-PHASE MULTILEVEL-THSEAF

A Transformerless Hybrid series active filter configuration is considered in this paper in order to avoid current harmonic pollution along the power line caused by a single-phase diode bridge rectifier load, followed by an inductor LNL in series with a resistor RNL. The sequences of the modulation are presented in Fig. 7.

A. Modeling of Transformerless Series Active filter

According to Fig. 3, and the average equivalent circuit of an inverter developed in [19], the small-signal model of the proposed configuration can be obtained. Kirchhoff's rules for voltages and currents, as applied to this system, provide us with the differential equations.

Thereafter, d is the duty cycle of the upper switch of the converter leg in a switching period, whereas $\bar{v}$ and $\bar{i}$ denotes the average value in a switching period of the voltage and current of the same leg. The mean converter output voltage and current are expressed by (10) and (11) as follows.

$$\bar{v}_O = \frac{(2d-1)V_{DC}}{m} \qquad (10)$$

$$\bar{i}_{DC} = m\bar{i}_f \qquad (11)$$

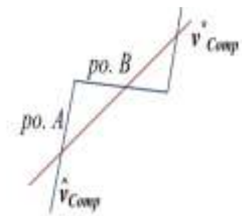


Fig. 5.Compensating voltage versus the reference signal.

According to the scheme on Fig. 3, the arbitrary direction of i_f is chosen to go out from the H-bridge converter. For dynamic studies the accurate model is considered.

$$mV_{DC}=L_f\frac{di_f}{dt}+V_{comp} \quad (12)$$

$$r_c C_f\frac{dv_{comp}}{dt}=-V_{comp}+r_c(i_f+i_s) \quad (13)$$

The state-space small-signal ac model could be derived by a linearized perturbation of averaged model as follow:

$$\dot{x}=AX+BU$$

Hence we obtain:

$$\frac{d}{dt}\begin{bmatrix} i_f \\ \hat{v}_{Comp} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & -\frac{1}{r_c C_f} \end{bmatrix} \times \begin{bmatrix} i_f \\ \hat{v}_{Comp} \end{bmatrix} + \begin{bmatrix} \frac{V_{DC}}{L_f} & 0 \\ 0 & \frac{1}{C_f} \end{bmatrix} \times \begin{bmatrix} m \\ i_s \end{bmatrix} \quad (15)$$

The output vector is then

$$Y=cx+Du \qquad (16)$$

$$Y=[0\ 1]\times\begin{pmatrix} i_f \\ V_{comp} \end{pmatrix} \quad (17)$$

By means of (15) and (17), the state-space representation of the model could be obtained. The second order relation between the compensating voltage and the duty cycle could be reached as follows.

$$C_f \frac{d^2 v_{comp}}{dt^2} + \frac{1}{rc}\frac{dvcomp}{dt} + \frac{1}{L_f} v_{comp} = \frac{V_{DC}}{L_f} m + \frac{di_s}{dt} (18)$$

This model could then be used in developing the converter's controller and its stability analysis.

IV. CONTROL ALGORITHM OF THE SYSTEM

The Multilevel Transformerless Hybrid series active filter configuration considered in this work is taking advantage of an NPC converter to reduce passive components rating while, delivering a high-quality compensating voltage. The controller strategy implemented in this paper is based on a Proportional plus resonant controller to generate IGBT's gate signals. The reference signal applied to the P+R regulator is created by two detection block taking care of the voltage and current issues respectively as presented in the following control diagram.

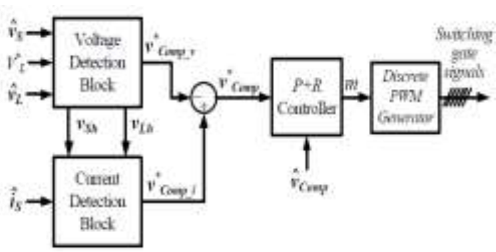


Fig. 6. Control system architecture scheme for P+R.

In this Rapid Control Prototyping (RCP) application, the whole controller is implemented on the Opal-RT device, where the controller is run on a fixed time step size determined in the core of the paper in Table I. The inputs of the controller described in Fig. 8, are measured using the Opal-RT probes. The output signals of the controller are the switching gate signals produced over the digital output of the real-time simulator. These signals are then passing through opt isolator board to enable semiconductor gate driver's control.

As the compensating voltage reference is an oscillating signal with several harmonic components, the P+R regulator has numerous advantages over other control approaches. To develop the controller, the average equivalent circuit of the converter is used with the small-signal model of the proposed configuration to analyze the effects of delays on the transient response of the compensator. The proposed control strategy takes advantages of both a proportional and resonant controller to generate gating signals.

The transfer function of the controller with a multi-resonant property is given by:

$$G_{P-R}(s) = K_P + \sum_h^n = 1,3,5,7 \dots\dots \frac{2k_{rh}w_{c}s}{s^2+2w_c s+(h.w^2)} (19)$$

Where h is the harmonic order, $Kp$and $Krh$are gains, and $h\omega$is the resonant frequency and $\omega C$is the cutoff frequency. Their values are depicted in Table I. The frequency responses with a delay time are depicted in Fig. 9, where the Bode diagram shows the superiority of the PR controller over the system without regulation and with a PI regulator.

To implement the controller on the digital simulator the transfer function should be obtained by discretization via numerical integration. To obtain the discrete equivalent of a transfer function via numerical integration, one should apply appropriate numerical integration techniques depending on the sensitivity and stability requirements to the system differential equation [20].

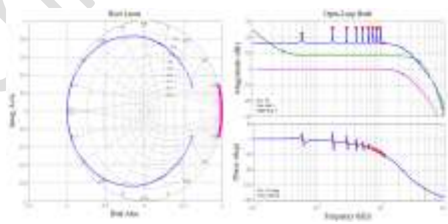


Fig. 7.Frequency response of the system with a 40 µs delay time; using the PI controller, P+R controller, and with a closed-loop controller. (a) Root Locus diagram. (b) Bode diagram.

The P+R controller function is then calculated, where z is the variable in the z-domain and T is the sampling time constant also known as step-time TS in Matlab environment. By performing the Z-transform, using the Tustin or bilinear approximation based on the trapezoidal rule, on (19), the discrete transfer function is achieved as follow. The frequency variable "s" is replaced by the following term.

$$S\text{-}\frac{2.(z-1)}{T(Z+1)} \quad ,S^2 - \frac{4(Z-1)^2}{T^2(Z+1)} \quad (20)$$

This results in the following discrete transfer function in the z-domain.

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$$G_{P+R}(z) = K_P + \sum_{h=1,3,5,7,\dots}^{n} \frac{2K_{rh}\cdot\omega_C\cdot z^2\cdot T - K_{rh}\cdot\omega_C\cdot T}{(1+\omega_C T+(h\omega T)^2)z^2+\left(\frac{(h\omega T)^2}{2}-2\right)z+1-\omega_C T+\frac{(h\omega T)^2}{4}} \tag{21}$$

According to the two developed discrete function, one can implement either of them for a real-time simulation or a practical experiment on a digital controller. Meanwhile, the choice of gains is tied with the stability study of the transfer function. The gains should be chosen depending on the sampling time imposed by the digital controller, and the behavior of the system itself. In a general rule; the more the sampling time *T*, has a smaller value, the more the chance to reach a stable system is observed.

IV.SIMULATION RESULTS

The proposed THSeAF configuration was simulated in MATLAB/simulink using the discrete time of T_s=10µs. The combination of a single-phase nonlinear load and linear load with a rated power of 2kVA with a 0.74 lagging 120Vrms 60Hz variable source is used. THSeAF connected in series to the system compensates the current harmonics and voltage distortions. A gain G = 8Ω (=1.9 p.u) was used to control current harmonics. During the grid's voltage distortion, the compensator regulates the load voltage magnitude, compensates the current harmonics and corrects the PF. The load voltage VL THD is 0.44%, while the source voltage is highly distorted ($THDV_s$ = 1.45%).

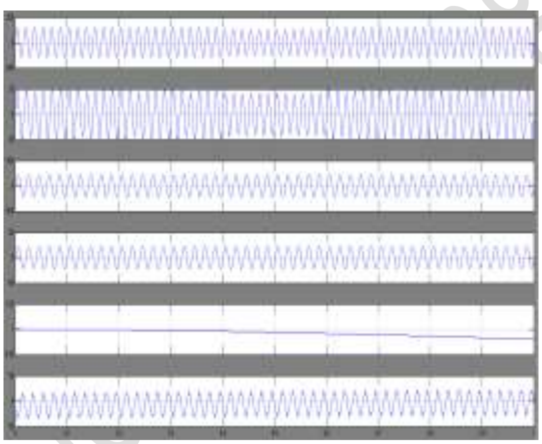

Fig.8.Simulation waveforms for voltage sag.(a).Source Voltage Vs,(b).Source current is, (c).load voltage $V_{L,}$ (d) load current $i_{L,}$(e) Active-filter voltage Vcomp, and (f) Harmonic current of the passive filter i_{PF}.

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 compensator shows high efficiency in normal operation where the total compensator losses including switching, inductor resistances, and damping resistances are equal to 44 W which is less than 2.5% of the system rated power. While cleaning the source current from harmonics and correcting the PF, the compensator regulates the load terminal voltage.

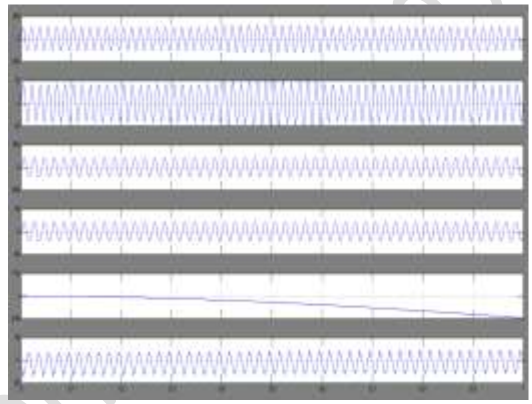

Fig.9.Simulation waveforms for voltage swell.(a).Source Voltage Vs,(b).Source current is, (c).load voltage $V_{L,}$ (d) load current $i_{L,}$(e) Active-filter voltage Vcomp, and (f) Harmonic current of the passive filter i_{PF}.

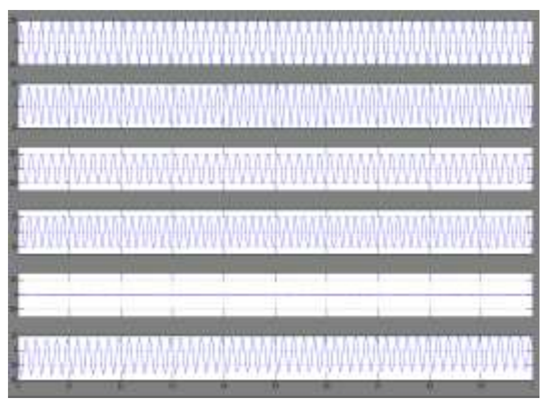

Fig.10.Simulation waveforms for voltage swell.(a).Source Voltage Vs,(b).Source current is, (c).load voltage $V_{L,}$ (d) load current $i_{L,}$(e) Active-filter voltage Vcomp, and (f) Harmonic current of the passive filter i_{PF}.

THD for current

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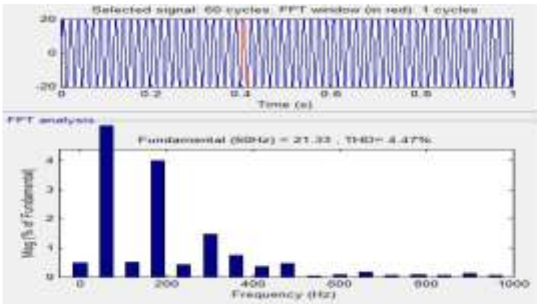

Fig.10.Total harmonic distortion for current.

THD for voltage

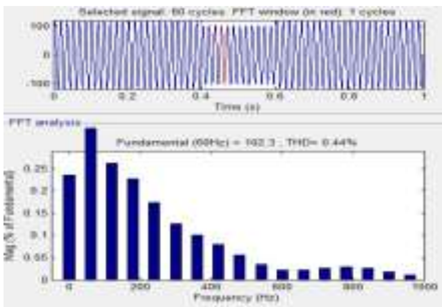

Fig.11.Total harmonic distortion for voltage.

In Fig.10 & 11 shows the total harmonic distortion levels in the current and voltage waveforms. The THD for current and voltage are 4.47% and 0.44%.The THSeAF reacts at once to this variation and does not interfere its operation functionality. To valuate the compensator during utility perturbation, the power source becomes distorted. The source current become cleaned of the majority of harmonics are in the load current and has a unity power factor. The THSeAF defends the sensitive loads and maintain a sinusoidal and regulated voltage across the PCC of loads with a 0.44% of distortion. The compensator ought to inject power to maintain the load PCC voltage regulated at the desired level. The harmonic content and THD factor of the source utility and load PCC shows improvement in THD, the load draws polluted current waveforms. Although the grid's voltage is polluted, the compensator in a hybrid approach regulates and maintains harmonic-free load voltage. The various levels of THD for proposed system and existing system are shown in Table-3.

TABLE-2

	Load voltage V_L(v)	Load current I_L(A)	Grid voltage V_s(v)	Grid current I_L(A)
Proposed system	4.6%	6.9%	0.44%	4.47%
Existing system	6.6%	19.7%	25%	5.2%

V. Conclusion

Renewable energy sources that are proliferating very rapidly are connected to the grid via resonant filters that may also interact with the grid impedances and can cause undesired EMI and resonance phenomenon. Therefore the necessity of maintaining clean decoupled power is becoming an important issue since electric power quality is usually measured at generation, distribution and load levels. To improve power quality, a Multilevel-THSeAF was developed in this work based on the five-level NPC configuration. The key novelty of the proposed topology includes power quality improvement in a single residential building that may result to the enhancement of the global power system. Moreover, the configuration can regulate and improve the load voltage and when connected to a renewable auxiliary DC source, the topology is able to counteract actively to the power flow in the system similar to a UPS. Having a constant and distortion-free supply at load PCC, it was denoted that the active compensator responds well to source voltage variations. Furthermore, this compensator eliminates source harmonic currents and improves grid power quality with no need to use the typical bulky series transformer. 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. The proposed transformerless configuration was simulated and experimentally validated.

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