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Power Quality Improvement of Single Phase Distribution System Using Hybrid Series Active Power Filter

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***Abstract*— In this paper a hybrid series active filter for power quality issues are discussed .power quality issues include source current harmonic elimination due to nonlinear load and grid initiated power quality problems like voltage sag/swell compensation, voltage harmonics injected from grid etc. Thus the compensation is done with the help of small rated series active filter and tuned shunt passive filter. Controller used is a digital controller which has both voltage loop and current loop cleaning grid side current harmonics with small compensation gain and improving power factor at the load and doing reactive power compensation. Shunt passive filter used here is mandatory and is needed to remove voltage distortion and cleaning grid side current harmonics. Sliding mode controller with notch harmonic detection technique is used for controlling the series active filter. Simulation is done on MATLAB/SIMULINK tool with 6.2kVA load.**

***Index Terms*— Hybrid series active filter, current harmonics, power quality, sliding mode control.**

I. Introduction

With the developments of power electronic equipments and nonlinear loads, the power quality has been deteriorating in distribution system. Current harmonics can cause serious harmonic problems in distribution feeders for sensitive consumers. Some technology options have been reported in order to solve power quality issues. Initially, lossless passive filters have been used to mitigate harmonics and compensate reactive power in nonlinear loads. However, passive filters have the demerits of fixed compensation, large size and resonance with the supply system.

Active filers have been explored in shunt and series configurations to compensate different types of nonlinear loads; nevertheless, they have some drawbacks. As a case in point, their rating is sometimes very close to load, and thus it

Becomes a costly option for power quality improvement. Many researchers have classified different types of nonlinear loads and have suggested various filter options for their compensation. In response to these factors, a series of hybrid filters has been evolved and extensively used in practice as a cost effective solution for the compensation of nonlinear loads. State-of-the-art power electronic technology has enabled engineers to put active filters into practical use. Many shunt active filters consisting of voltage-fed pulse width modulated (PWM) inverters using IGBT or GTO thyristors are operating successfully in all over the world. These filters have provided the required harmonic filtering, reactive power compensation etc [2].

Due to smart grid implementation there is a constant increase in the use of nonlinear load like switched mode power converter, drives etc. Thus it causes serious power quality problems due to power quality problems it increases losses and can cause serious failure of some sensitive electrical equipment, and reduce the efficiency [4,5]. Thus it calls for additional protection for voltage sag /swell, voltage distortion, current harmonics etc. series active filters are less spread than shunt active power filters and received fewer industrial investigations and little research is dedicated to such compensators due to their complex operational procedure and configuration. The complex configuration and need of isolation transformer had decelerated

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their industrial widespread application in distribution system. [6,7]

In order to eliminate the disadvantages put forwarded by the series active power filter; a hybrid series active power filter is proposed and it is a cost effective solution and active filter needs only less rating .Thus it provide reduced switching noise and reduced electromagnetic interference. In this scheme filtering operation is divided between two filters like active filter provide high impedances for almost all harmonics and passive shunt filter provide low impendence for particular harmonics and it offers high impedances to all other harmonics and fundamental component.

Dynamic voltage restorer and series active power filter are same and differ with their control strategy used. A transformer less hybrid series active power filter is proposed in this paper such as to overcome the disadvantages of isolation series transformer. [8]

The single-phase Transformerless-HSeAF presented in this paper is capable of cleaning the grid side from current harmonics generated by non-linear loads, while it restores and provides a clean sinusoidal voltage for the load. Advantage of the proposed configuration relies on the fact that harmonic currents leading to voltage distortions could be efficiently compensated. In addition, this configuration could contribute to the integration of renewable in distributed generation systems with high penetration of renewable energy sources and more importantly it permit soft integration of charging stations in the residential and distribution network.[1]

The topology is used in single phase if it is used for compensation in three phase system it is recommended that we use individual such system for three phases and is controlled independently. Thus setup shows great capability for current harmonics elimination, power factor correction, reactive power compensation and voltage sag/swell compensation even under change of grid inductance. For simulation purpose it uses a 6.2kVA load in combination of nonlinear load and linear load. Thus for noncompensated system it is seen that the grid has 92% harmonic and it also causes 12% voltage distortion at the load end. The effectiveness of the compensation is shown also by grid perturbation with injected voltage harmonics at the source side .Thus reactive power compensation and power factor correction are done at the load end.

II. SYSTEM ARCHITECTURE

The figure 1 shows hybrid series active filter connected to the single phase system and thus it has got bank of shunt tuned passive filter for current harmonic elimination which provide low impendence path for particular harmonics and high impendence for all the harmonics and fundamental component. Series active filter with sliding mode control is below which uses a transformer less series active filter thus provide cost effective solution and even if we increase the number of switches transformer less configuration is much better than the one uses transformer for compensation. The auxiliary source connected to the series active filter will provide active power needed for compensation. The LC filter used with the series active filter provides low order harmonics elimination. The control used here senses source current, load voltage, source voltage and inverter output voltage.

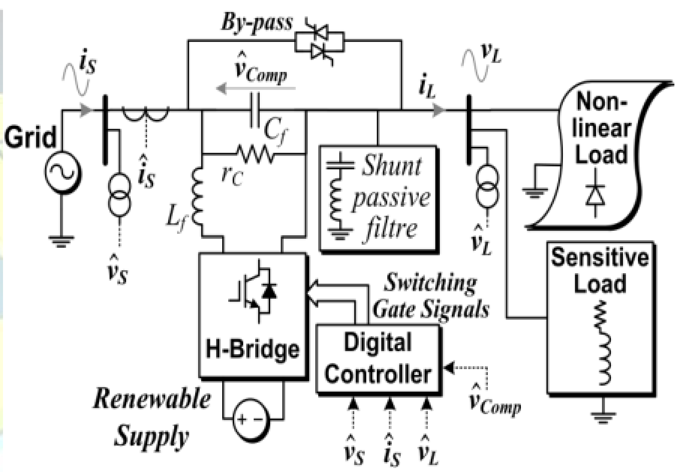

Fig 1. Transformer less hybrid series active power filter connected to the single phase system.

A. *Principle of proposed current compensation approach*

A voltage 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. The Norton equivalent circuit is depicted in Fig. 2. In this paper the common Norton equivalent is chosen to follow major related papers. The principle of such modeling is documented in [3]. In this paper the approach to achieve optimal behavior during the time the grid is perturbed is implemented on the controller. The use of a passive filter is mandatory to compensate current issues and maintaining a constant voltage free of distortions at the load terminals [1]. The non-linear load is modeled by a resistance representing the active power consumed and a current source generating harmonics current.

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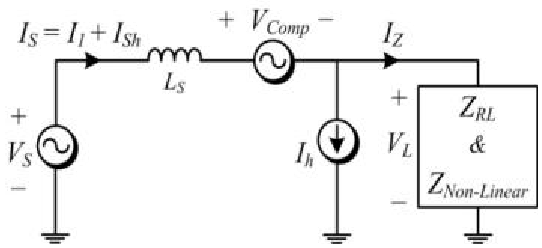

Fig 2.single phase Norton equivalent phasor model for VSC type of loads

The impendence of the load i.e., Z_L is the combined effect of both nonlinear load and linear load. The series active filter generates compensation voltage through the sensing of source current, load voltage, source voltage. Digital controller described in the figure uses a sliding mode control for compensation. Current harmonics are eliminated through the use of a small compensation gain which converts current into voltage. Assume grid is injected with harmonics

$$V_S = V_{S1} + V_{Sh} \quad (1)$$

$$I_S = I_{S1} + I_{SH} \quad (2)$$

$$V_L = V_{L1} + V_{LH} \quad (3)$$

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

Suing Kirchhoff's law, the following equation is depicted for both the fundamental and harmonics,

$$V_S = I_S Z_S + V_{COMP} + V_L \quad (5)$$

$$V_{L1} = Z_{L*} I_{S1}, \quad V_{LH} = -Z_L(I_{SH} - I_H) \quad (6)$$

By substituting (4) in (5) source current harmonics become zero. Thus under this approach even under source voltage distortion the source current will remain clean of any harmonic components.

The rating of the compensator is designed based on the required power consumers desire to restore during sags in the grid supply. For the 6.2 kVA load, in order to restore a 40% voltage sag, and at the same time compensating source current harmonics and correcting the power factor following sizing is suggested. The auxiliary supply should be designed accordingly as: $S_{DCsource}$ = 6.2×40% = 2480VA. The converter should transfer the load RMS current and have the following characteristics: $I_{Converter} = I_L$ = 6.2 kVA/230Vrms = 27Arms. The nominal voltage of the converter is then $V_{Converter}$ = 2480VA/27Arms = 91 Vrms. The DC bus voltage is then required to be $V_{DCsource}$ >120 Vdc and the more DC voltage is, the compensation will have a better performances. The bank of series resonant tuned shunt passive filters, assuming a 20% of 5_{th} harmonic component, should have the following parameters: V_{SPF} =230Vrms with a rated current of I_{SPF} = 5.4A. To have an optimized design a primary study of the nonlinear load characteristic is required and then the same design process should be taken for the other tuned branches if required.

III. Modeling and Control of The THSeAF

For the modeling of the series active power filter along with shunt passive filter a single phase grid is modeled using combination of nonlinear load with linear load .Thus nonlinear load uses a diode bridge rectifier and parallel combination of resistance and capacitance. The combination of non linear load and linear load are designed for 6.2kVA and accounts for 92% of the current harmonic at the source current and 12% of the voltage distortion at the load end.

A .Modeling of Transformerless Series Active filter

Simulink model of the proposed configuration is shown in the fig .3

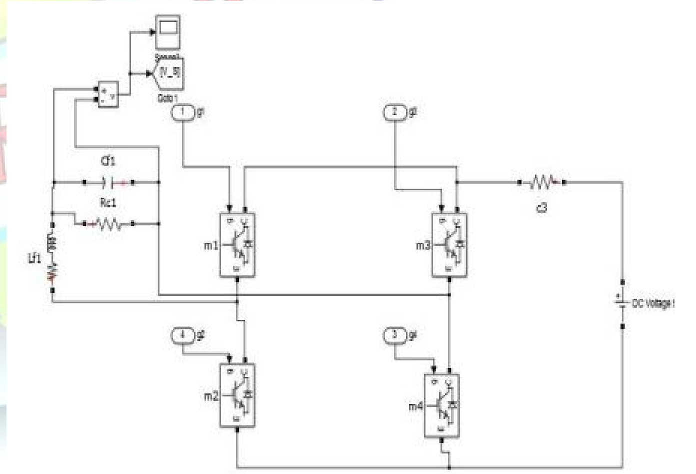

Fig 3. Simulink model of single phase full bridge inverter.

Thereafter, *d* is the duty cycle of the upper switch of the converter leg in a switching period, whereas V and I denotes the average values in a switching period of the voltage and current of the same leg. The mean converter output voltage and current are expressed by (7) and (8) as follow.

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$$V = (2d-1)\, V_{dc} \quad (7)$$

$$I_{dc} = m * I_f \quad (8)$$

For dynamic studies the accurate model is considered.

$$mV_{DC} = L_f \frac{di_f}{dt} + v_{Comp} \quad (9)$$

$$r_C C_f \frac{dv_{Comp}}{dt} = -v_{Comp} + r_C(i_f + i_S) \quad (10)$$

The state space model is derived using linear perturbation and is as follows:

$$\dot{x} = Ax + Bu \quad (11)$$

Hence we obtain:

$$\frac{d}{dt}\begin{bmatrix} \bar{i}_f \\ \bar{v}_{Comp} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_f} \\ \frac{1}{C_f} & -\frac{1}{r_C C_f} \end{bmatrix} \times \begin{bmatrix} \bar{i}_f \\ \bar{v}_{Comp} \end{bmatrix} + \begin{bmatrix} \frac{V_{DC}}{L_f} & 0 \\ 0 & \frac{1}{C_f} \end{bmatrix} \times \begin{bmatrix} m \\ i_S \end{bmatrix} \quad (12)$$

The output vector is then:

$$y = Cx + Du \quad (13)$$

$$y = [0 \quad 1] \times \begin{bmatrix} \bar{i}_f \\ \bar{v}_{Comp} \end{bmatrix} \quad (14)$$

By using (14) and (12) second order relation between the compensating voltage and duty cycle could be reached as follow.

$$C_f \frac{d^2 v_{Comp}}{dt^2} + \frac{1}{r_C}\frac{dv_{Comp}}{dt} + \frac{1}{L_f} v_{Comp} = \frac{V_{DC}}{L_f} m + \frac{di_S}{dt} \quad (15)$$

This is used for the converter control.

B. Sliding-mode controller

The controller outer loop consists of two parallel sections which are notch harmonic extractor technique. First part is for voltage regulation and second part is for current harmonic compensation. Thus controller operates with two loops i.e., for maintaining load voltage regulation with reduced load voltage harmonics and cleaning the grid current from current harmonics and providing reactive power compensation and power factor correction. Compensation gain G is used so as to convert current harmonics into voltage harmonics.

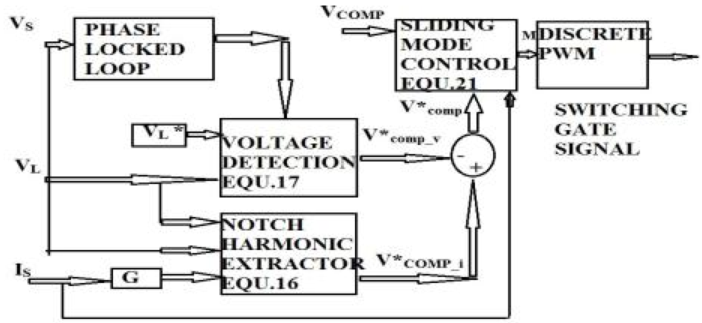

Fig .4. Control system architecture scheme.

The PLL used here generates reference angular frequency in synchronized with the source voltage utility (wt).The notch harmonic extractor is implemented through the following equation;

$$V_{COMP\_i} = +GI_{SH} - V_{LH} + V_{SH} \quad (16)$$

The compensation gain 'G' used here converts the source compensating current harmonics into relative voltage .generated $\mathbf{V_{COMP\_i}}$ is required for cleaning grid current form harmonics.
The voltage sag/swell are compensated with the help of following equation.

$$vcomp\_v = [kp(vl^* - vl) + ki\int (vl^* - vl)\, dt]\sin(wt) \quad (17)$$

Where *vl** is set by the operator.

Final compensation voltage reference is reached by combination of above two voltage components and is written as follows:

$$V^*_{COMP} = -V_{COMP\_V} + V_{COMP\_i} \quad (18)$$

The remaining part of the control is done by using sliding mode control. Sliding mode control is a nonlinear control it is a robust type control method that alters the dynamics of a nonlinear system by applying discontinuous control signal that forces the system to slide along a sliding surface. A switching function described as (σ) which is the indication of whether the states are inside the system or outside the system also it indicates the distance of state form the sliding surface. If the states comes inside of the sliding surface switching function equals to a constant zero value and if the states is outside of the switching surface then the switching function becomes nonzero.
If there exist a controller to move the trajectory close to the sliding modes one then the system can be said to be under stable. Whenever the sliding mode achieve zero value and system

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remains on the sliding mode surface and sliding mode trajectory σ is kept constant, so that its derivation remain equal to zero .

$$\sigma = (d/dt + \lambda)e \qquad (19)$$

Where the error is

$$e = (Vcomp - v*comp) \qquad (20)$$

The equivalent duty cycle m_{eq} derived from equation (15) is written as follows;

$$m_{eq} = \frac{C_f L_f}{V_{DC}}\left[L_f \frac{d^2 v^*_{Comp}}{dt^2} + \lambda \frac{dv^*_{Comp}}{dt} + \left(\frac{1}{r_C C_f} - \lambda\right)\frac{d\hat{v}_{Comp}}{dt} + \frac{1}{L_f C_f}\hat{v}_{Comp} - \frac{1}{C_f}\frac{di_S}{dt}\right] \qquad (21)$$

The control law is determined as ,

$$M = M_{EQ} - K_1 * Sat(\sigma) \qquad (22)$$

The stability condition can be analysed through lyapunov function and K_1 value should be greater than zero .the convergence rate of the state variables will depend on this selection.

TABLE I
CONFIGURATION PARAMETER

symbol	definition	value
vs	linea phase to neutral voltage	230 Vrms
f	system frequency	50Hz
Ls	equivalent supply inductance	150µH
RnL	non linear load resistance	40 ohms
CnL	non linear load capacitance	1000uf
SL	linear load apparent power	1200VA
PLf	linear load power factor	70%
Cf	switching filter capacitor	5uf
Lf	switching filter inductance	12mh
Rf	switching filter damping resistance	75
L5	fifth harmonic tuned inductor	2.18mh
C5	fifth harmonic tuned capacitance	200uf
L7	seventh harmonics tuned inductor	2.18mh
C7	seventh harmonic tuned capacitance	102uf
Ts	sampling Time	20us
Fpwm	pwm frequency	20KHz
G	control gain for harmonic current	8
K1	sliding mode parameter	3
Vdc	dc supply source	250 V

IV. SIMULATION RESULTS

Simulation is done using MATLAB/SIMULINK toolbox and for simulation a 6.2kVA nonlinear load with linear load is considered. Whereas 5kVA nonlinear load with 0.8pf lagging is considered and 1.2kVA linear inductive load with 0.7pf is used for simulation. Simulation is done with 20µs sampling time.

The compensator is connected in series to the system compensates the current and voltage related issues. Thus with the simulation it is proved that the compensator compensates for grid initiated problems and load initiated problems. Thus transformer less hybrid series active power filter is preventing load current with high THD to flow into the utility and thus accounts for correcting power factor at the load. As from the figure 5. It is seen that voltage harmonics are injected into the source voltage between times 0.2 to 0.4 sec thus through voltage detection loop and notch harmonic extractor used in the control loop it is seen that grid initiated voltage harmonics problems are not affecting the load voltage .that is load voltage is clean of harmonics between 0.2 to 0.4 sec. Again with the voltage sag/swell problems initiated through the grid are also compensated through the voltage detection loop used with accurate tuning of proportional gain and integral gain.

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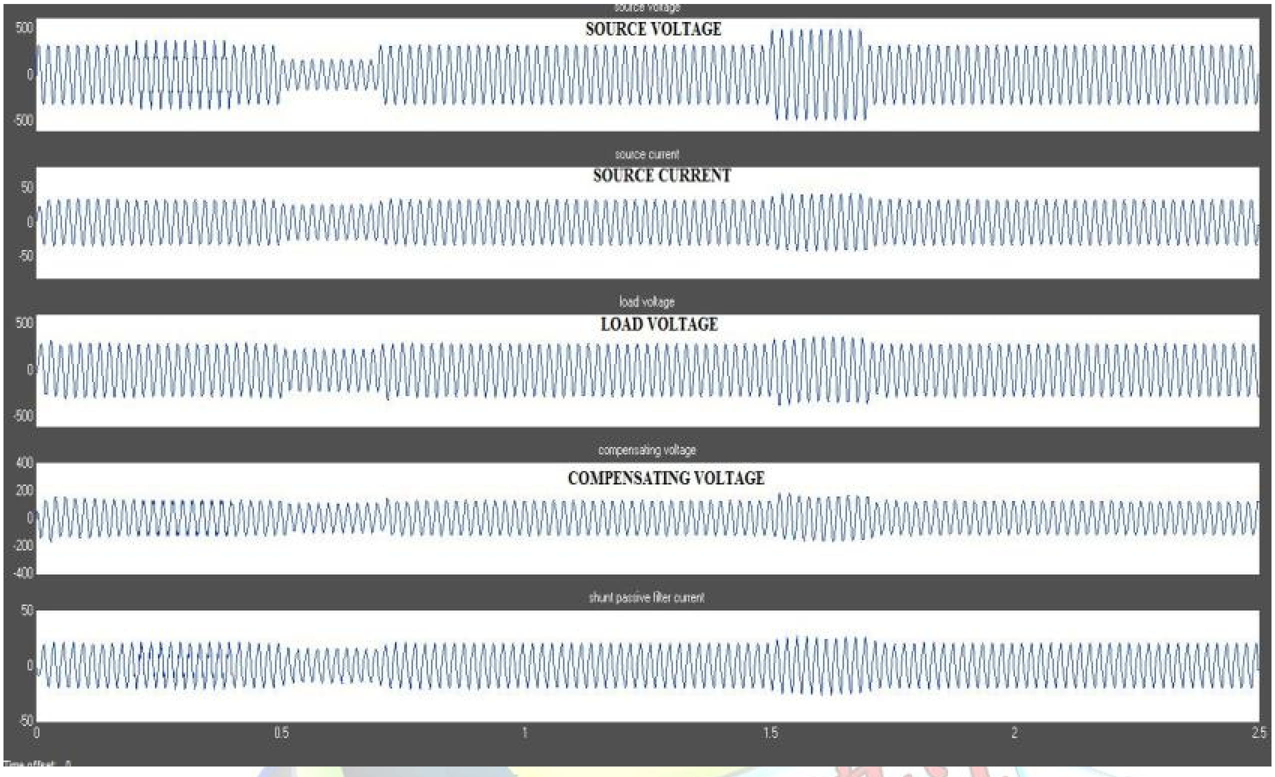

Fig .5 .Simulation of the system with the THSeAF compensating current harmonics and performing a voltage restoration on the load

The load voltage THD is maintained to a low value by the perfect tuning of the shunt passive filter .shunt passive filter tuning is a one time tuning and independent of other parameters in the system.

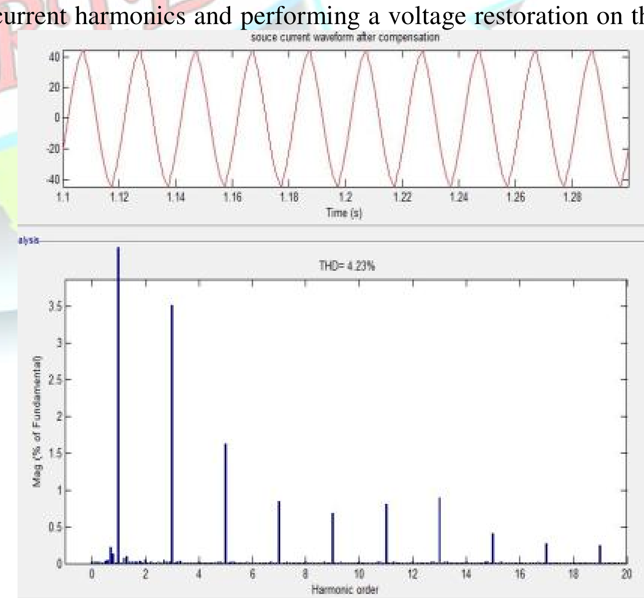

Fig 6. Source current harmonics after placing the compensator

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Source current harmonics after placing the compensator is reduced to be less than 5% and it is 4.23% only .Thus the challenging task of reducing the current harmonics from 92% to 4.23% is carried out here. Through the perfect tuning of the shunt passive filter the current harmonics can be reduced to a greater extent. Voltage harmonics initiated through the grid is 20% and after placing the compensator it is now reduced to less than 5% and is of 3.69% only. Christo Ananth et al.[5] presented a brief outline on Electronic Devices and Circuits which forms the basis of the Clampers and Diodes.

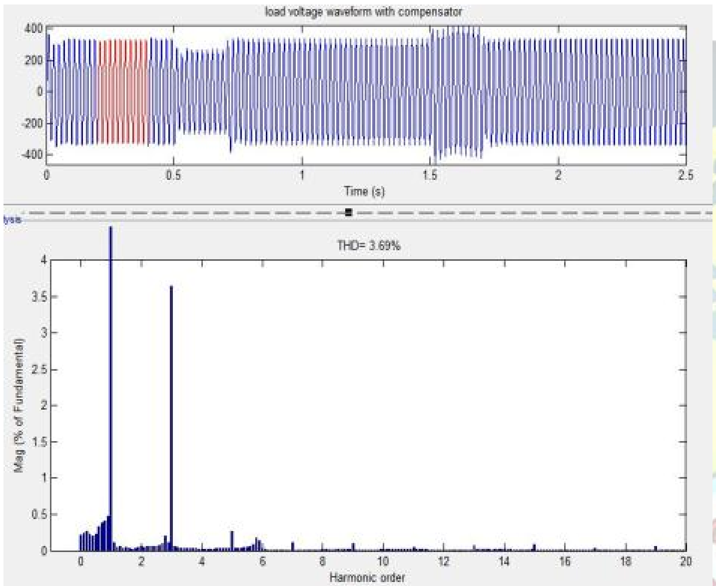

Fig 7. Load voltage harmonics after placing the compensator.

The PLL is of great importance in the single phase application and PLL is able to detect zero crossing events even during source voltage distortion as reference where tuned low pas filter are used for filtering distortion and extracting fundamental.

The compensation gain used in this simulation uses only less compensation gain and thus compensation gain of 8ohm is good with eliminating source current harmonics and making the power factor to almost unity. The dc voltage used in this simulation also of very good because it only uses a dc voltage of 250V and thus with only a 250V dc supply the system is able to clean the source current harmonics and maintain constant magnitude load voltage.

The compensator with both series active filter and shunt passive filter compensate for both current harmonics and voltage harmonics and it forces the current to come in good power factor with the load voltage. The compensator efficiency is very good and accounts for very less compensator loss and it may be neglected.

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

TABLE II
THD COMPARISON BEFORE AND AFTER COMPENSATION

1	THD
source current harmonics without compensator	92.00%
source current harmonics with compensator	**4.23%**
load voltage harmonics without compensator	20.00%
load voltage harmonics with compensator	**3.69%**
voltage sag /swell compensated : **yes**	

V. SUMMARY

Transformerless hybrid series active power filter using sliding mode control is proposed in this thesis work and it compensates for source current harmonics due to nonlinear load .grid initiated problems like voltage harmonics, voltage sag/swell problems are compensated. The digital controller used in this thesis work uses voltage detection loop and notch harmonic extractor. The stability of the system is guaranteed with the help of sliding mode control and analysed with lyapunov criteria .The reactive power exchange with the utility is done through series active filter and load voltage is maintained constant. power factor of the load are also corrected through the combined series active filter and shunt passive filter .harmonic free voltage is delivered to the residential load terminal. The filter uses a chattering less sliding mode control with added boundary layer and boundary layer thickness is suitably selected .control gain and control bandwidth are suitably selected so as to provide stable chattering less operation. The advantage of the thesis work is the system uses only less dc voltage for compensation. The system also has inherent short circuit current limiting capability. It can replace UPQC device for a long run.

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VI. FUTURE SCOPE

Sliding mode control used provides stable working condition but sliding mode control is a complex control its design calculation are complex and its operation procedure is also complex producing chattering with excitation of un modeled dynamics. Thus PR controller or such simple control can be done .the grid side fault should be analysed and a fault current limiter can be done incorporated with the series active filter. In this paper control gain ,control bandwidth ,boundary thickness are chosen with trial and error method but auto tuning of sliding mode control parameters can be done which can provide better tracking and less chattering control.

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