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EXPERIMENTAL INVESTIGATION ON A HYBRID SERIES ACTIVE POWER COMPENSATOR TO IMPROVE POWER QUALITY OF TYPICAL HOUSEHOLD

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ABSTRACT

With the recent development in the power electronic devices, the use of power electronics in controlled Variable Speed Drives (VSD) is increasing in industrial and domestic applications. In recent years, significant attention has been focused on line side harmonics because they overload power network infrastructure, affect quality of the grid, cause reliability problem in equipment and waste energy. Therefore mitigations of harmonics have been considered has important research issues in power system.

In this project, a transformer less hybrid series active filter using a sliding-mode control algorithm and a notch harmonic detection technique are implemented on a single-phase distribution feeder. This method provides compensation for source current harmonics coming from a voltage fed type of nonlinear load (VSC) and reactive power regulation of a residential consumer. The realized active power filter enhances the power quality while cleaning the point of common coupling (PCC) from possible voltage distortions, sags, and swells initiated through the grid.

I. INTRODUCTION

The forecast of a smart grid associated with the constant increase of switch-mode power converters ,drives as well as domestic and industrial non linear loads has created a serious concern on the power quality of the future distribution power systems as shown in Fig.1, where nonlinear loads have deteriorate the power quality [1,2]. These distortions increases losses and can cause serious failure of some sensitive electrical equipment, and reduce the efficiency [3-5]. Moreover, the points of common coupling (PCC) will require additional protection to avoid voltage distortions, sags, swells [6, 7] and therefore ensure a reliable supply. To mitigate power quality issues, there exist three categories of compensators [8, 9]; the conventional and widespread used passive filters [10, 11] widespread distribution system.

Fig.1. Typical residential consumer with electronic loads, and measured electric car (Nissan Leaf®) voltage and current patterns connected to a level-2 AC charging station, and an iPhone4s charger

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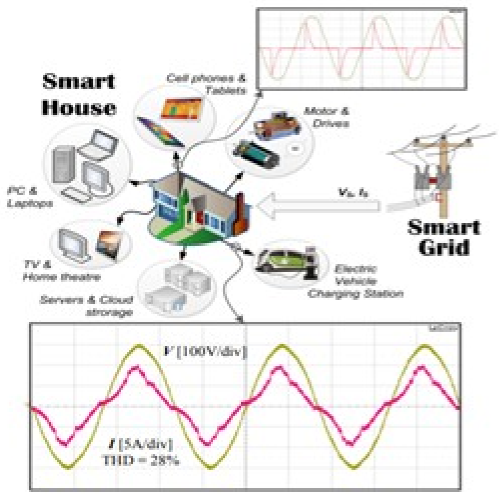

Fig.1. Typical residential consumer with electronic

Table I Comparison Of Power Quality Improving Compensators

		Passive Filters	Active Filters				
	Power quality Parameters	Operation	Shunt AF	Series AF	Series AF/ DVR operation	Hybrid Series AF	Transformerless Hybrid Series AF (THSeAF)
Load Initiated Problems	Current Harmonic	Yes	Yes	Yes	No	Yes	Yes
	Reactive Power Compensation	Yes	Yes	Yes	No	Yes	Yes
	Current Unbalance	No	Yes	Yes	No	No/ Yes *1	No/ Yes *1
Grid Initiated Problems	Voltage Distortion	Yes	No	No	Yes	Yes	Yes
	Voltage Unbalance	No	No	No	Yes	Yes/ No *2	Yes/ No *2
	Voltage Sags	No	No	No	Yes	Yes	Yes
	Voltage Swells	No	No	No	Yes	Yes	Yes
	Voltage Interruption	No	No	No	Yes	Yes	Yes

*1 "Yes" if the Voltage unbalance at the load is not selected for compensation

*2 "No" if the Current unbalance is been compensated

Active Filters are classified, based on their electrical connection to the system. Table I gives a preview of various active filters and their ability over power quality problems.

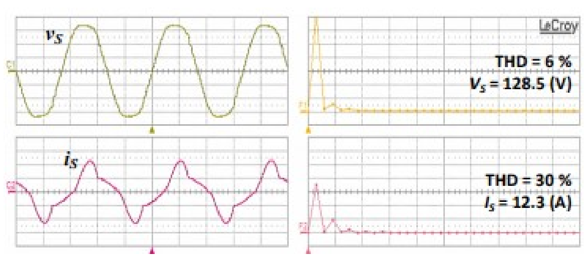

Fig. 2. Terminal voltage [50V/div] and current [10A/div] waveforms of a 1.6-kVA load without compensation (the THSeAF is by-passed).

Voltage and current harmonic detection methods along with the adapted sliding mode controller are explicitly described. To evaluate the configuration and the control approach, some scenarios are simulated while experimental results performed in laboratory validate the study in this paper.

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The single-phase Transformer less-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.

II. SYSTEM ARCHITECTURE

The filter is used to reduce the harmonics and improve the power quality. The filter that is connected to the system should be controlled effectively such that its response characteristics are as desired. Among the different available filter configurations, hybrid power filter with series APF and a parallel passive filter is used in this project. The control circuit of the series connected APF is designed such way that the voltage injected by the APF compensates the harmonics and also enhances the performance of the shunt connected passive filter. The control strategy of the hybrid power filter is explained in detail in this chapter.

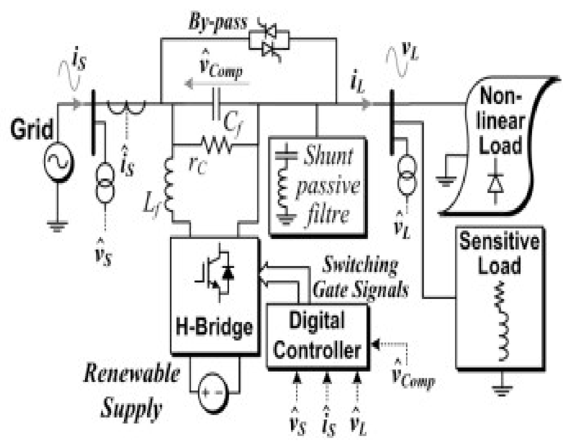

Fig: THSeAF Connected to the Single-Phase System.

III. PRINCIPLE OF THE PROPOSED CURRENT COMPENSATION APPROACH

Accordingly, the impedance Z_L is the equivalent of the nonlinear ($Z_{\text{Non-linear}}$) 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 ***G*** to achieve low level of current harmonics [8].The gain ***G*** is proportional to the current harmonics (I_{sh}) flowing to the grid. Assuming the grid contains voltage distortions, the equivalent circuit for the fundamental and harmonics are

$V_S=V_{s1}+V_{sh}$ (1)

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

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

$V_{\text{Comp}}=GI_{Sh}-V_{Lh}+V_{Sh}$ (4)

where I_Z represents the load current in Z_L

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

$V_S=Z_SI_S+V_{\text{Comp}}+V_L$ (5)

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$V_{L1}=Z_L I_{S1}, V_{Lh}=Z_L(I_{Sh}-I_h)$ (6)

By substituting the fundamental of (6) into (5), the source current at fundamental frequency is obtained:
$I_{S1} = (V_{S1}/(ZS + ZL))$ (7)

By substituting (4) into (5) for the harmonic components, the harmonic source current is reached as follows:
$V_{Sh}=Z_S I_{Sh}+GI_{Sh}-V_{Lh}+V_{Sh}+V_{Lh} \quad \rightarrow I_{Sh}=0$ (8)

By introducing (8) into the harmonic component of the load PCC voltage (6), the following equation is achieved:
$V_{Lh}=-Z_L I_h$. (9)

The rating of the compensator is designed based on the required power consumers desire to restore during sags in the grid supply. For the 1.6-kVA load, in order to restore a 40% voltage sag, and at the same time, compensating source current harmonics and correcting the PF following sizing is suggested. The auxiliary supply should be designed accordingly as $S_{DCsource}$=1.6×40%=650 VA. The converter should transfer the load RMS current and have the following characteristics. $I_{Converter}=I_L$ = 1.6kVA/120,V_{rms}=13A_{rms}. The nominal voltage of the converter is then $V_{Converter}$=650VA/13 A_{rms} = 50V_{rms} [4]. The dc bus voltage is then required to be $V_{DC\ source}$ >70Vdc 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 fifth harmonic component, should have the following parameters: V_{SPF} = 120V_{rms} with a rated current of I_{SPF} = 2.6 A. 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.

IV. MODELING AND CONTROL OF THSeAF

A THSeAF 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 a capacitor *CNL* in parallel with a resistor *RNL*. The THSeAF which structure is illustrated in Fig. 4.3acts as a controlled voltage source connected in series with the loads between the grid and the PCC.

Modeling of Transformer less Series Active Filter

According to Fig.4.1 and the average equivalent circuit of an inverter developed, the small-signal model of the proposed configuration can be obtained, as shown in Fig. 4.2. Kirchhoff's rules for voltages and currents, as applied to this system, provide us with the differential equations including the *LC* filter.

Thereafter, *d* is the duty cycle of the upper switch of the converter leg in a switching period, whereas $\bar{v}$ and $\bar{i}$ denote the average values in a switching period of the voltage and current of the same leg, respectively. The mean converter output voltage Fig.4.2. Small-signal model of transformer less HSeAF in series between the grid and the load.Fig.4.3. Control system architecture scheme. and current are expressed by (10) and (11) as follows:

$\bar{v}_O = (2d - 1)\, V_{DC}$ (10)
$\bar{i}_{DC} = m\, \bar{i}_f$. (11)

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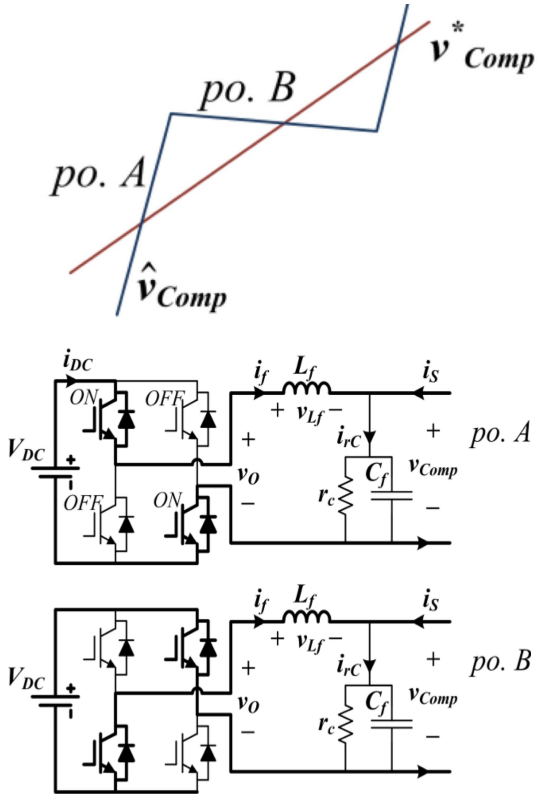

Fig. Small-signal model of transformerless HSeAF in series between the grid and the load.

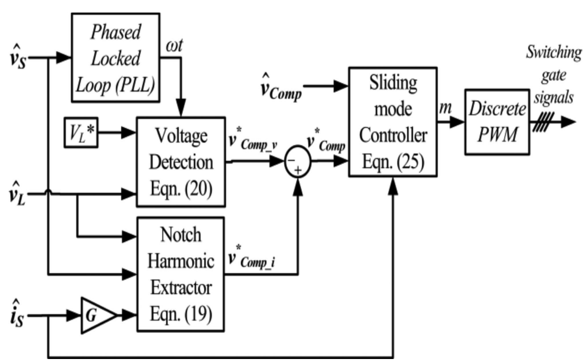

FIG :Control System Architecture.

Sliding-Mode Controller

In the source current regulation block, the notch filter extracts magnitude of the fundamental and its phase degree, leaving harmonics and the reactive component. The control gain *G* representing the impedance of the source for current harmonics should be enough to clean the grid from current harmonics fed through the nonlinear load. The generated reference voltage $v_{\text{comp}\,i}$ required to clean source current from harmonics,

$v_{\text{comp}\,i} = +Gi_{Sh} - v_{Lh} + v_{Sh}$.

The proportional and integrator gains of the PI regulator and ˆ $V_L$is the magnitude of ˆv_L. The final compensating voltage reference is reached by combination of the stated components related to current issues and voltage issues.

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$v_{comp} = -v_{compv} + v_{comp\ i}$.

V. INTRODUCTION TO MATLAB

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation.

Matlab language

This is a high-level matrix/array language with control flow statements, functions, data structures, input/output, and object-oriented programming features. It allows both "programming in the small" to rapidly create quick and dirty throw-away programs, and "programming in the large" to create complete large and complex application programs.

Matlab simulink

Simulink, an add-on product to MATLAB, provides an interactive, graphical environment for modeling, simulating, and analyzing of dynamic systems. It enables rapid construction of virtual prototypes to explore design concepts at any level of detail with minimal effort.

VI. DESIGNING OF THSeAF FOR NONLINEAR LOAD

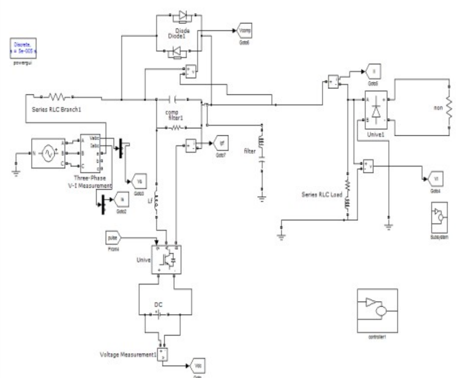

Figure 4.6: THSeAF connected to non linear load

The circuit shown in the above figure is designed with the help of simulink in matlab. A single phase supply is supplied to the system through three phase supply lines. The harmonics are inserted at the input terminals and the voltage and current measurements are connected to the non linear load to observe the output waveforms of the system.

Subsystem in non linear load

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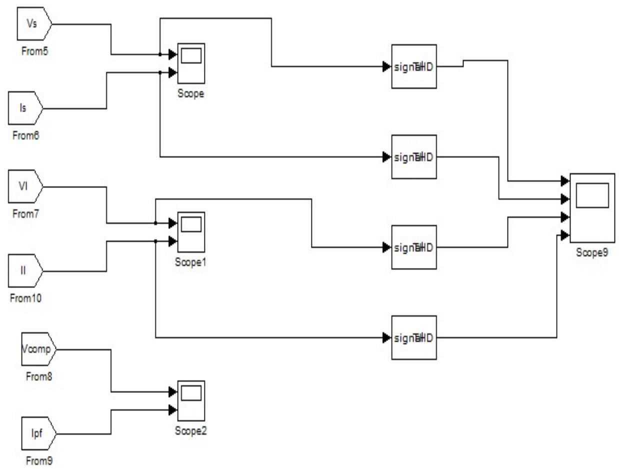

Figure 4.7:Subsystem

From the figure 4.6, the harmonics are injected at the input source and the results for the input waveform is observed at the scope. Similarly, the output waveforms that is at the load side is observed at the scope 1.The output waveforms of the V_{comp} and I_{pf} are obtained at scope 2.The THD responses of all the outputs are obtained at the scope which is at the end of the circuit.

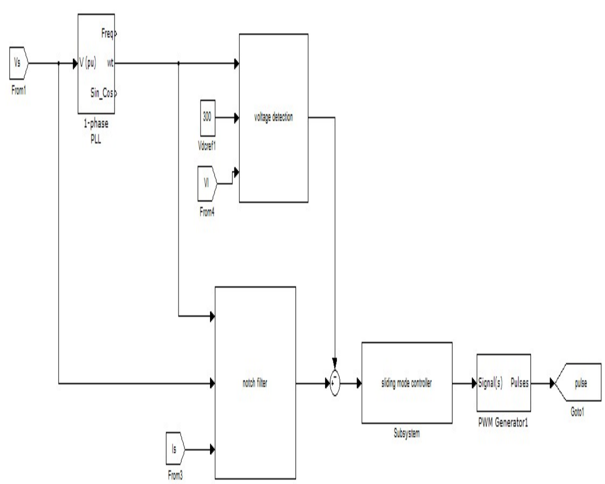

Figure 4.8: Sliding mode control in Subsystem

VII. SIMULATION AND RESULTS

This section presents results of the THSeAF configuration in MATLAB/Simulink using a time steps of Ts = 10 μs. Then, for experimental implementation, the controller is loaded on the dSPACE/dsp1103 for fast control prototyping[6]. To achieve reliable and error-free implementation, the complete control loop was executed every 40 μs

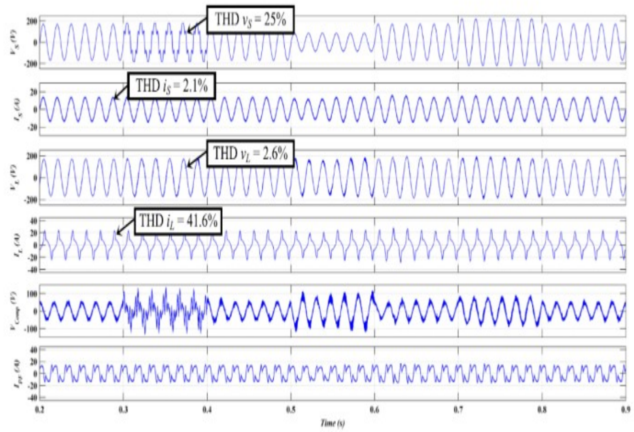

Figure 5.1: Simulation of the system with the THSeAF compensating current harmonics and performing a voltage restoration on the load.

Source voltage v_S. (b) Source current i_S. (c) Load voltage v_L. (d) Load current i_L(e) Active-filter voltage

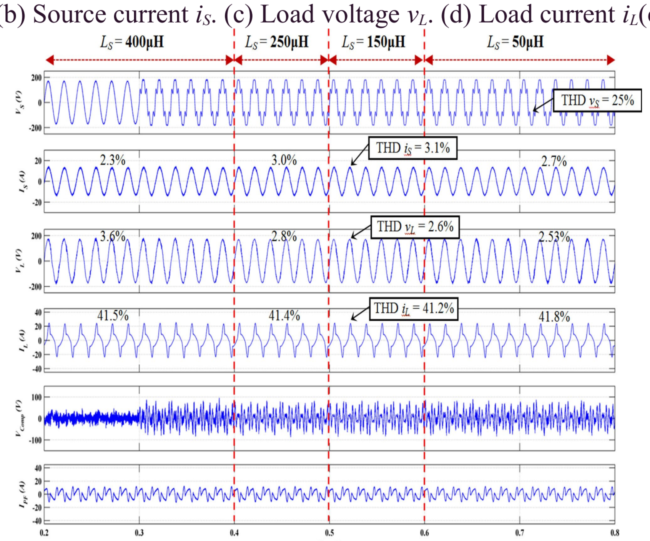

Figure 5.2: Compensation of a perturbed source voltage under grid impedance variation

The results of various scenarios similar to those effectuated in the simulation are verified in Fig. 5.3, showing the compensator during steady state operating with parameters described in Table 5.1. The THSeAF isolates a highly polluted load harmonics from the utility. The compensator maintains the load's voltage regulated with constant amplitude and free of all kinds of distortions independently of the grid condition.

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Symbol	Definition	Value
v_s	Line phase-to-neutral voltage	120 Vrms
f	System frequency	60 Hz
L_S	Supply equivalent inductance	150 μH
R_{NL}	Nonlinear Load resistance	40 Ω
C_{NL}	Nonlinear Load capacitance	1000 μF
S_L	Linear load apparent power	864 VA
PF	Linear load power factor	70%
L_f	Switching ripple filter inductance	5 mH
C_f	Switching ripple filter capacitance	2 μF
r_C	Switching ripple damping resistor	50 Ω
F_5	Fifth-order shunt passive filter	150 μF, 2.5 mH
F_7	Seventh-order passive filter	50 μF, 2.5 mH
F_{HPF}	High-pass filter	2μF
T_S	dSPACE Synchronous sampling time	40 μs
f_{PWM}	PWM frequency	10 kHz
G	Control gain for harmonics current	3 Ω
K_1	Sliding-mode parameter	3
V_{DC}	DC auxiliary power supply voltage	130 V

Table 5.1: Experimental Configuration Parameter

The PLL is of great importance in single-phase applications and should be suitable for a real-time and discrete implementation. The developed PLL in this paper is able to detect zero crossing events even during source voltage distortion as reference, where tuned low-pass filters are employed to filter distortions and extract the fundamental. The line current shows dramatic improvements in its THD, while the THSeAF is operating in a hybrid approach.

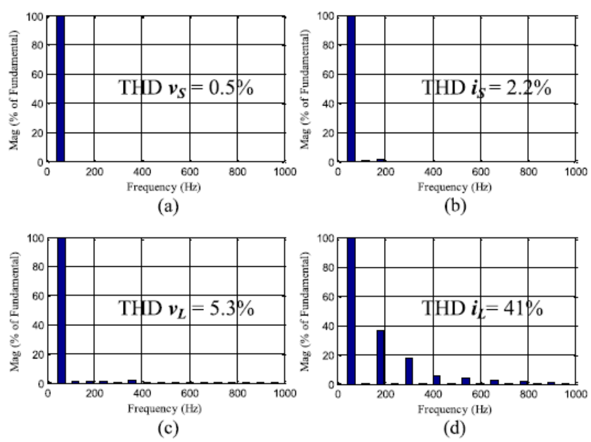

Figure 5.4: Harmonic contents in percentage of fundamental when THSeAF in operation.
(a) and (b) Source voltage and current. (c) and (d) Load voltage and current.

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 to reach a unity PF.

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The THSeAF prevent existing perturbation on the grid's voltage to propagate into the load PCC. Thus, it protects sensitive loads by maintaining the voltage sinusoidal and regulated. Moreover, in a worst possible scenario presented the already distorted utility's voltage is subjected to voltage magnitude variation.

Measures	Load		Grid Utility (Source)	
	Voltage (V), V_L	Current (A), I_L	Voltage (V), V_S	Current (A), I_S
THD (%)	5.2	40.5	13	4
Fund. (rms)	120	11.9	116	10.8
Active power, P (W)	1155		1243	
Reactive power, Q (var)	617		80	
Power, S (VA)	1428		1252	
Power Factor, PF	0.8		0.99	
Compensator, THSeAF	$S_{\text{Comp}} = +88W - j537$ var			

Table 5.2 Laboratory Measured Value and Power Flow Analysis

During a voltage sag and swell, the auxiliary source supplies the difference of power to maintain the magnitude of the regulated load-side voltage. The harmonic content and THD factor of the source utility and load PCC presented show dramatic improvements in THD [10], while the load draws polluted current waveforms. Furthermore, although the grid's voltage is polluted the compensator in a hybrid approach regulates and maintains a harmonics-free load's voltage.

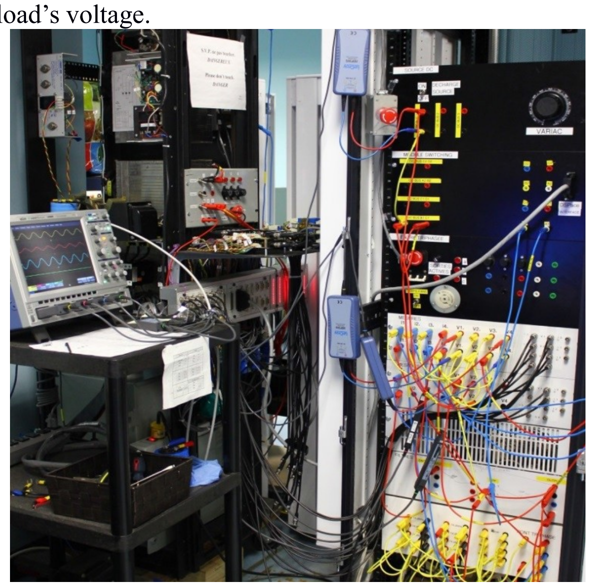

Fig.Laboratory set up used for experiment

VIII. CONCLUSION

The demand for electric power is increasing at an exponential rate and at the same time the quality of power delivered became the most prominent issue in the power sector. Thus, the reduction of harmonics and improving the power factor of the system is of utmost important. In this project a solution to improve the electric power quality by the use of Active Power Filter is discussed [2].

Therefore, it is concluded that the hybrid filter consisting of series APF and a shunt passive filter is a feasible economic solution for improving the power quality in electric power system.

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