Technical Report

on

Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF)

(In House Case Study)

Prepared by

Dr. V. R. Kanetkar

(February 2015)

Shreem Electric Limited

(Plot No. 43-46, L. K. Akiwate Industrial Estate,

Jaysingpur, Dist. Kolhapur, Maharashtra)

Contents

List of Figures

Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF)

(In House Case Study)

1.0 Preface

The use of non-linear loads in industrial and other applications has substantially gone up or proliferated with IEEE, IEC, and EN standards coming up for making the supply conditions harmonically less distorted so that loads can work in tandem and stresses on T&D are reduced.

The current harmonics produced by the non-linear loads, apart from increasing upstream losses to some extent, cause other problems. These problems include (i) distortion of the incoming supply voltages beyond acceptable limits thus causing synchronization issues for other sensitive loads connected on same supply bus, and (ii) causing heating or resonance with Supply Short Circuit Inductance of capacitor banks connected on the same supply bus or on the same network through other transformers.

In many applications the reactive power control (dynamic or switched) and current harmonic control go hand in hand. If the dynamics of the load is less or restricted, it is possible to design current harmonic filters along with reactive power compensation without much of a difficulty.

However, it is extremely difficult to design passive current harmonic filters unless they consume minimum of 10% of the operating VA / kVA as the VAr / kVAr of the load. Thus, where requirement of reactive VAr does not exist, the design of passive filters becomes extremely difficult. These are the applications which involve use of diode rectifiers and almost constant firing angle based thyristor converters.

Thus, with near zero reactive power compensation requirement for the supply, the current harmonic reduction in supply currents remains a cause of worry through passive current harmonic filters. Apart from difficulties in designing passive current harmonic filters as indicated above for such applications, there is a fear in user’s mind that these filters can cause resonance with Supply Short Circuit inductance and result in damaging most of his protective gear as well as connected load controllers.

Active Filters came in existence to fill up mainly this gap or fix this issue related to near zero reactive power compensation required for supply and reduction of current harmonics under such a situation. Additionally these filters removed the fear of any possible resonance in the system from the user’s mind and also offered total as well as individual current harmonic reduction along with dynamic reactive power compensation to an extent if found necessary. These filters, however, have high cost tag and the maintenance is equally costly as it involves experience in dealing with power electronics and digital electronics together with requisite knowledge of power systems and switchgear.

The question then comes back as to how one should deal with this situation? The answer lies in producing passive current harmonic filters which can be designed for near zero reactive power compensation requirement of the supply with “no resonance” condition ensured through its design, filters which satisfy current harmonic reduction requirement as per standards or as per user specification, and filters which are reliable and economical and filters which do not require highly qualified manpower to maintain it (more specifically fit and forget).

The Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF) is a custom built product [1] (patent applied or filed) which can be designed to meet the above stated necessary current harmonic reduction objectives at reduced cost and offering high reliability.

The case study presented below shows how such a filter (ZRPPCHF) can be designed and applied for zero reactive power demand to meet ≤ 5% current distortion in an LV 433 V system. The ZRPPCHF can be designed for any LV to HV voltage directly without use of any step down transformer which makes it highly economical (unlike the case with Active Filter which requires step down transformer typically beyond 690 V supply voltage).

2.0 Objective

- To design the Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF) for 50 kW three-phase, diode rectifier load so that incoming supply line current harmonic distortion is ≤ 5% as per IEEE 519
- To implement the entire system in Matlab, based on the design, and check the design validation through system simulation for given current distortion
- To implement the entire system with hardware, based on the design, and once again check the design validation experimentally for given current distortion
- To confirm that the total VAr / kVAr to be drawn by the filters is close to zero through simulation and experimental testing of the entire system
- To confirm that there is “No Resonance” with supply Short Circuit Inductance through design, simulation and experimental verification

3.0 System specifications

Three-phase, 50 Hz, 11 kV / 433 V, Delta / Star transformer supplying power to a three-phase diode rectifier of 50 kVA capacity, considered here as the non-linear load producing line current harmonics as 5, 7, 11, 13, and so on.

Supply Short Circuit Inductance measured through test, as per [2], is 240 μH on the secondary side (433 V side) of the transformer.

4.0 Brief understanding of system before designing the filters

The system considered here is three-phase, 11 kV / 433 V (Delta / Star 200 kVA transformer), 50 Hz, supply feeding a three-phase diode rectifier drawing approximately 50 kW / kVA. The Short Circuit Inductance measured / calculated for the supply (as per procedure explained earlier for establishing Short Circuit Capacity of supply network) is 240 μH on the secondary (433 V) side of the transformer. The rated current for the transformer on secondary side is 266.7 A. With 240 μH as the Short Circuit Inductance, the short circuit current works out as 3317.41 A.

This gives the Short Circuit Current to Rated Load Current Ratio (SCR) as 12.439 (=3317.41/266.7), which is less than 20. Thus, as per IEEE 519 standard the supply can bear 5% total current harmonic distortion if 266.7 A rated current flows on the secondary side.

On the other side, the three-phase diode rectifier connected on secondary side of 50 kVA rating, draws a fundamental current of 66.67 A. If this is the only load on the secondary of the transformer, the Short Circuit Current to Rated Load Current Ratio (SCR) would have been 49.76 (=3317.41/ 66.67), which is very close to 50, and can allow even 8% total current harmonic distortion as per IEEE 519 standard. However, the total current harmonic distortion is considered to be limited to 5% maximum for the diode rectifier load. Further, the diode rectifier theoretically has fundamental unity power factor and produces 5^{th}, 7^{th}, 11^{th}, 13^{th} … and so on as the current harmonics which are drawn from the supply.

Thus, the filters are to be designed in such a way that supply total current harmonic distortion is ≤ 5% and total VAr / kVAr to be drawn by the filters should be close to zero.

5.0 Values of filter components arrived through simple mathematical approach

For the requirements given above under "system specifications**"** and based on the filter design approach explained in earlier sections, the harmonic filters are considered for 5^{th}, 7^{th}, and 11^{th}, current harmonics for the rectifier. Values of the filter components worked out iteratively are as given below.

5^{th} harmonic filter:
C_{f5} = 170 µF, 25A L_{f5} = 2.4 mH, 25 A R_{f5} = 250 Ω, 60W R_{d5}= 70 kΩ, 10W

7^{th} harmonic filter:
C_{f7} = 170 µF, 20A L_{f7} = 1.23 mH, 20 A R_{f7} = 127 Ω, 60W, R_{d5} =70 kΩ, 10W

11^{th} harmonic filter:
C_{f11} = 170 µF, 18A, L_{f11} = 0.5 mH, 18 A R_{f11} = 51 Ω, 60W, R_{d5} = 70 kΩ, 10W

At 170 µF, the capacitive kVAr is approximately 10 kVAr. The discharge resistors for capacitors are based on 60 seconds discharge time.

Further, a common value of R_{fn} as 270 Ω is used for all filter inductances L_{fn}.

Compensating inductive filter bank:

C_i = 12.24 mF, 45A L_i = 19.9 mH, 45 A R_{fi} = 2 kΩ, 60W R_{di} = 1 kΩ, 10W

At 433 V, the compensating inductive filter bank draws approximately 41.75 A or 31.3 kVAr compensating the capacitive 3*10 = 30 kVAr of the harmonic filter banks.

The diode rectifier requires a 3.5% inductive impedance in line as commutation impedance, which means it should give 8.75 V (=0.035*250 V) at full load current of 66.67A. For this consideration, it requires a three-phase 420 μH, 70A inductance as the input inductance.

For delivering approximately 50 kVA, the output dc side resistance required is 7 Ω, 80A and inductance required is 8 mH, 80 A.

For 240 μH Short Circuit Inductance of the supply,, the inductive error impedance of 5% means -0.01884Ω for 5th harmonic, -0.026376Ω for 7th harmonic, and -0.041448 for 11th harmonic. The actual error impedances are 3.75% to allow for small variation in the available short circuit capacity of the supply network. The filter component values are chosen also based on availability of these components for the experimental check.

The low error impedances allow bulk of the respective harmonic currents to flow in those respective filter banks and negligible current in other harmonic filter banks.

6.0 Resonance check through design

For the 5th harmonic filter bank, the error impedance for 5th harmonic is -0.01413 Ω indicating it is inductive as desired to avoid resonance.

For the 7th harmonic filter bank, the error impedance for 7th harmonic is -0.019782 Ω indicating it is inductive as desired to avoid resonance.

For the 11th harmonic filter bank, the error impedance for 11th harmonic is -0.031086 Ω indicating it is inductive as desired to avoid resonance.

Further, for higher order harmonics, the impedances presented by each filter bank will be inductive **eliminating the possibility of resonance** with the supply short circuit inductance L_s. This will be further clear with the simulation results presented.

7.0 Simulation results

Fig. 1 gives the Matlab / Simulink model for the system incorporating the three-phase diode rectifier and the filter banks as covered above. Figure 2 gives the three-phase diode rectifier. Further, fig. 3 gives the filter banks for 5th, 7th, 11th, and the inductive VAr compensation filter banks used, and fig. 4 gives configuration for each of the filter bank.

Figure 5 shows simulation results for supply currents and the neutral current (scope 1 in fig. 6). The neutral current close to zero as expected due to three-phase diode rectifier load considered.

Figure 6 shows supply phase voltages after Short Circuit Inductance, supply phase “a” current, active power per phase, diode rectifier current, distortion of the total per phase load current, supply phase current distortion, and distortion of supply phase voltage after the Short Circuit Inductance (scope 3 in fig. 6). The active power drawn per phase is approximately 18 kW. The rectifier current distortion observed is nearly 25% and the supply current distortion is approximately 4.8%. The supply voltage distortion is close to 2%.

Figure 7 shows fundamental current displacement for the load current along with its power factor and fundamental current displacement of supply current along with its power factor (scope 2 in fig. 6). The respective values observed values are approximately 12^0, 0.976, 12.5^0, and 0.975.

The Matlab / Simulink simulation results confirm the following.

- The supply current distortion <5% against load current distortion of approximately 25% (as required by IEEE 519 standard for the given three-phase voltage of 433 V and Short Circuit Current to Rated Load Current Ratio (SCR) of 12.439).
- Incoming distortion observed as 2% which is also < 8%, the allowed distortion as per IEEE 519 (2014 latest version) standard for voltages ≤ 1 kV.
- The load and supply power factor is almost same (0.975 and 0.975 respectively) indicating that the filter banks work at close to Zero Reactive Power drawn from supply as desired.
- “NO” resonance with the supply Short Circuit Inductance, as desired.

8.0 Experimental set up and results

Experimental set up used is in line with figs. 1 for verification purpose using three-phase diode rectifier with output / dc side R-L impedance to generate required 120^0 square wave waveform (as seen in fig. 6). System details and specifications and design of filter banks remain same as explained earlier under the same headings. Resonance check carried out earlier based on the filter components also remains same as explained earlier. Actual real power drawn by the rectifier is approximately 53 kW. Major experimental results for the same system as discussed above are given in figs. 8 to 11.

Figure 8 shows practically observed three input currents of the three-phase diode rectifier captured on oscilloscope for the experimental set up. Figure 9 shows practically observed supply input current and rectifier input current captured. Figure 10 shows practically observed voltage and current waveforms for supply and rectifier captured indicating that the power factor is nearly same (or filter banks drawing nearly zero reactive power as desired). Figure 11 shows practically observed rectifier and supply input current distortion captured. Rectifier current distortion observed is 24.5% and supply current observed distortion is 4.9%.

Figure 12 shows the experimental set up and fig. 13 shows the 12.24 mF capacitor specifically developed for the experimentation.

The results show that the supply current harmonic distortion is less than 5%, no reactive power drawn from the supply, and there is no resonance with Supply Short Circuit Inductance as expected / desired. The experimental results, hence, by and large tally with the simulation results given in earlier part and confirm proper functioning of the Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF).

9.0 Conclusion

Based on the system specifications, the Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF) design details presented and there after the simulation and experimental results presented show / demonstrate that the objectives for the filter system stated at the beginning are achieved.

A Zero Reactive Power Passive Current Harmonic Filter (ZRPPCHF) can be a good, economical, and reliable alternative for filtering supply system current harmonics generated by non-linear loads. These passive filters do not require step down transformer and can be used effectively to constrain / obtain the supply current harmonic distortion within IEEE 519 standard limits or as specified by user for his system / application. This is made possible by suggested simple mathematical approach for the filter design(s) based on knowledge of the supply Short Circuit Capacity / Inductance and if not then by establishing the Short Circuit Capacity / Inductance.

References

[1] "A method and a system thereof for providing zero reactive power passive current harmonic filter for non-linear loads", Patent (application / reference no. 37/MUM/2014) filed by Shreem Electric Limited on 6th January 2014.

[2] V. R. Kanetkar, K. E. Shinde, and N. I. Dhang, " Importance of supply short circuit capacity and IEEE 519 standard for utilities and power consumers", CAPACIT 2014 Conference arranged by IEEMA at New Delhi between 20-21 November 2014, pp 141-146.

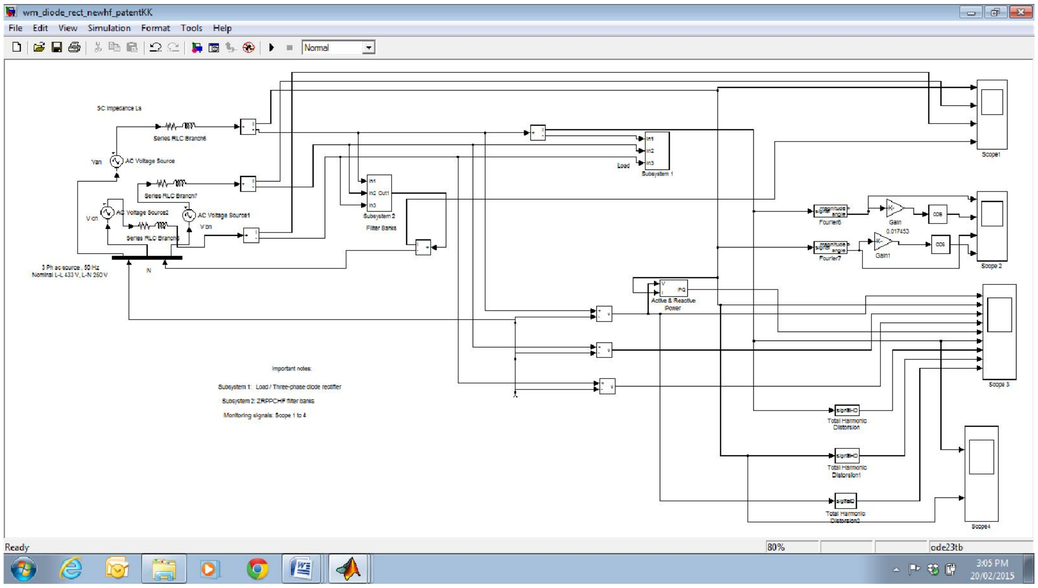

Figure 1: Matlab model

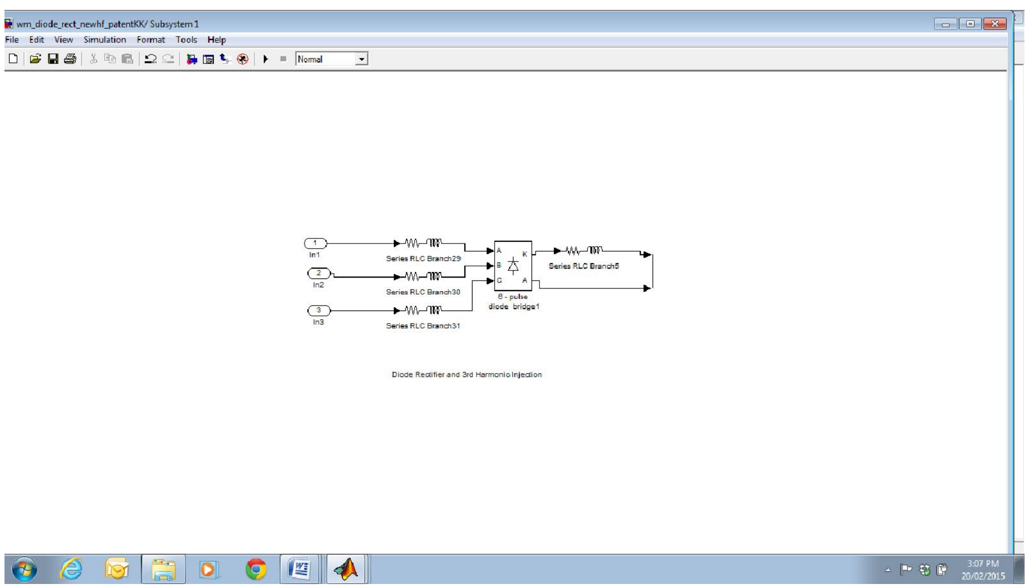

Figure 2: Three-phase diode rectifier (non-linear load)

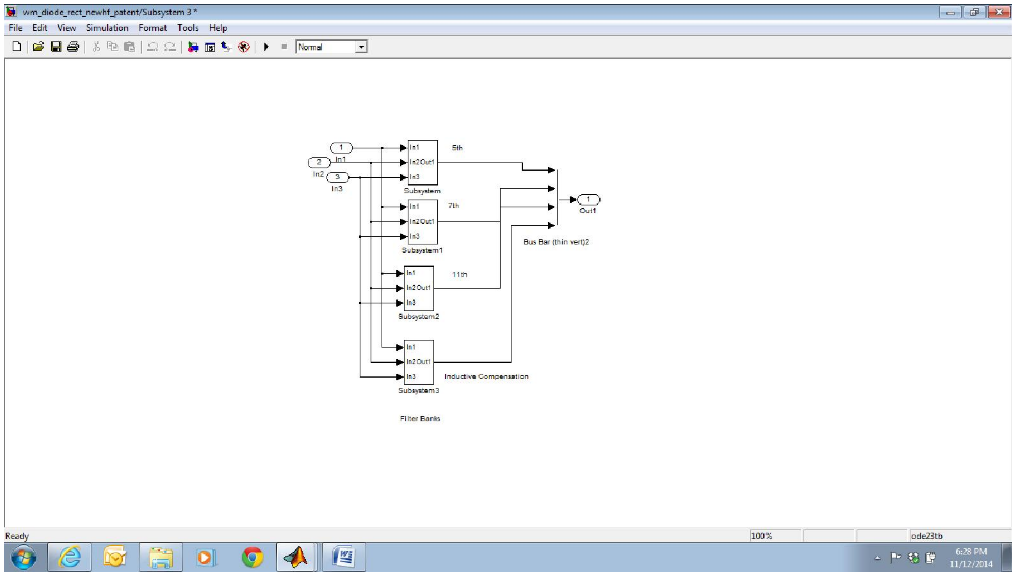

Figure 3: Harmonic filter banks

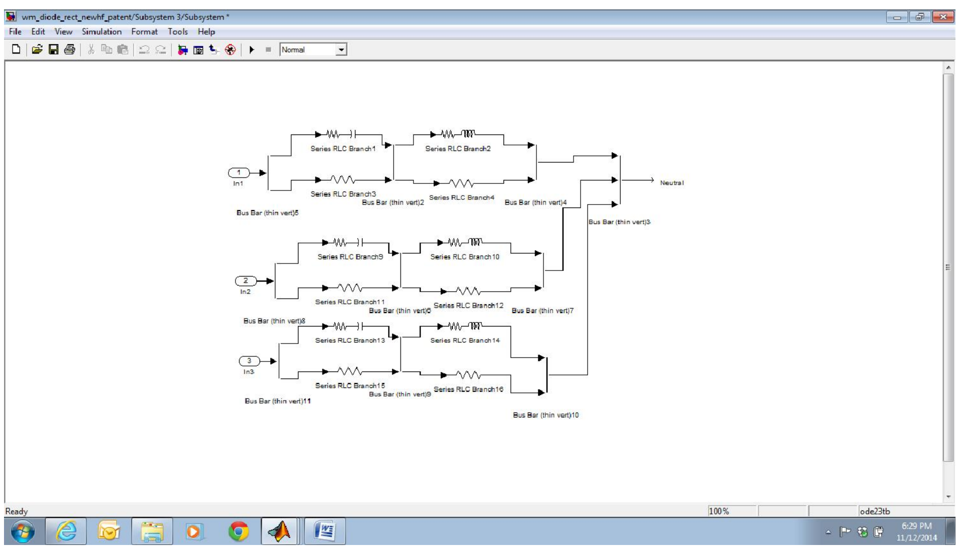

Figure 4: Harmonic filter bank configuration

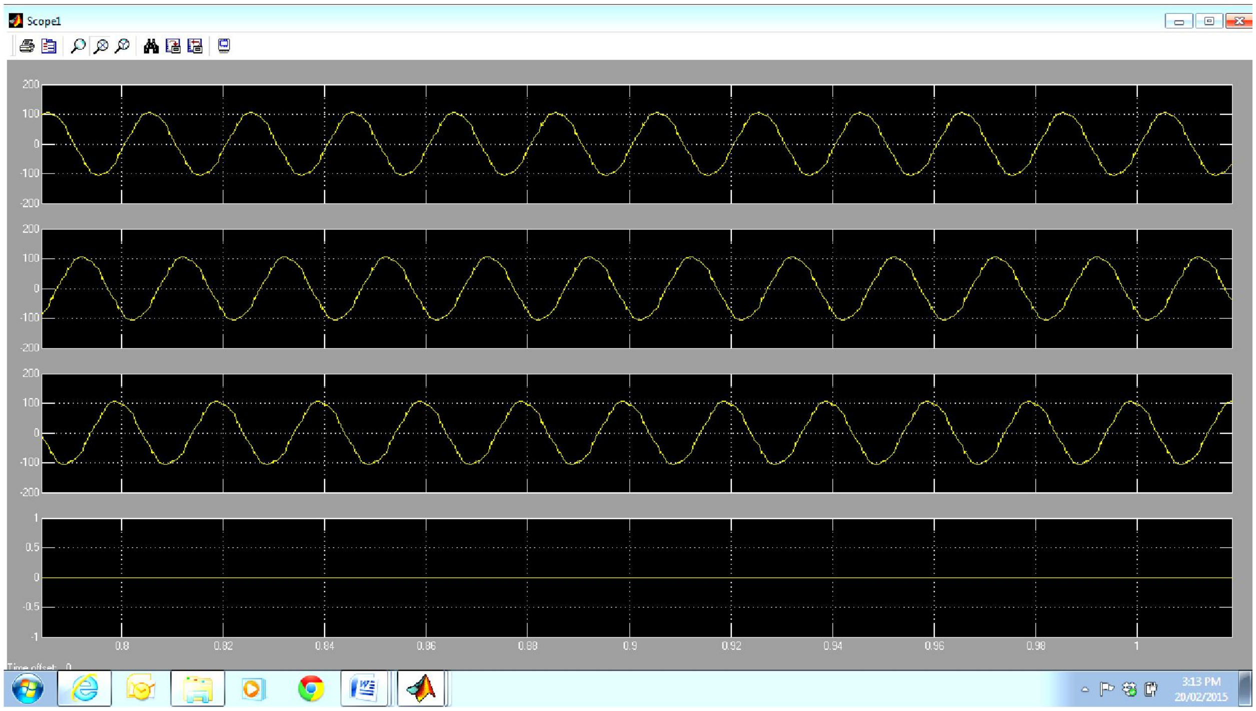

Figure 5: Supply currents and neutral current (through simulation)

Refer scope 1 in fig. 1

Ch1 to 3: supply currents

Ch4: Neutral Current close to zero as the load is three-phase diode rectifier

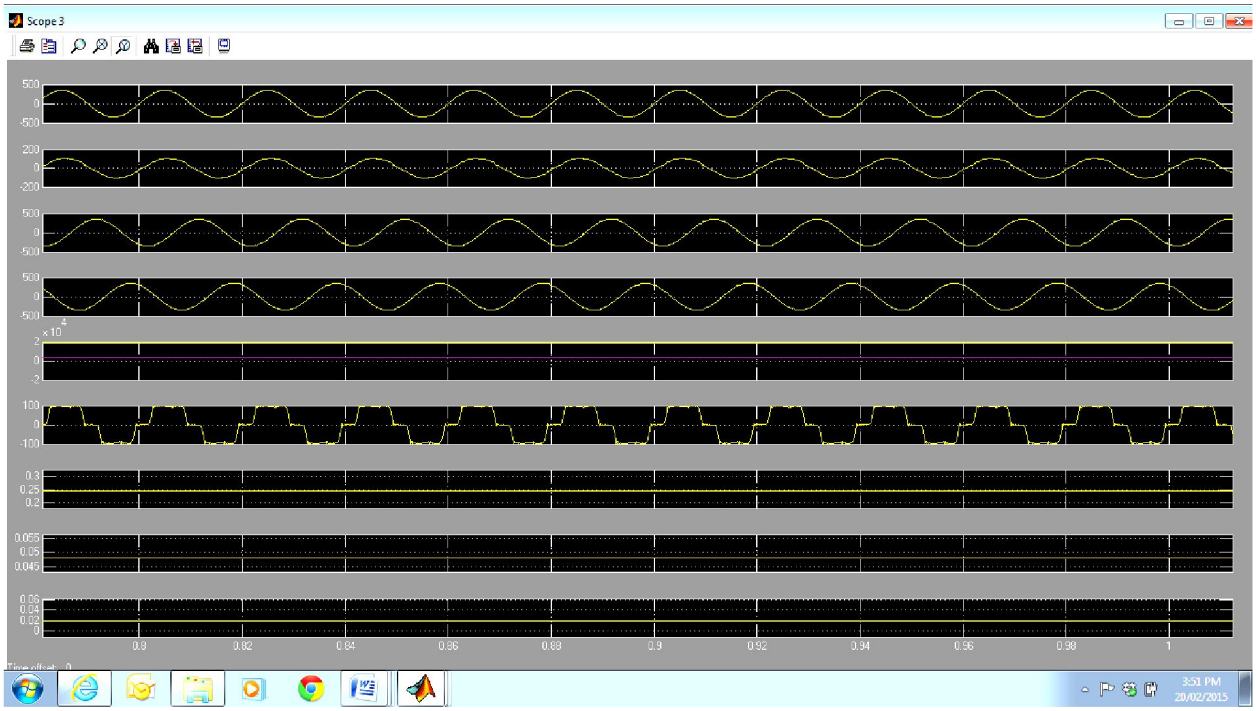

Figure 6: Supply phase voltage and current and their distortions, active power, rectifier input current and its distortion (through simulation)

Refer scope 3 in fig. 1

Ch1, 3, 4: Supply phase voltages after the Short Circuit Inductance

Ch2: Supply "a" phase current

Ch5: Active power per phase

Ch6: Diode rectifier input current (load current)

Ch7: Distortion of current in Ch6

Ch8: Supply phase current distortion

Ch9: Distortion of supply phase voltage after the Short Circuit Inductance

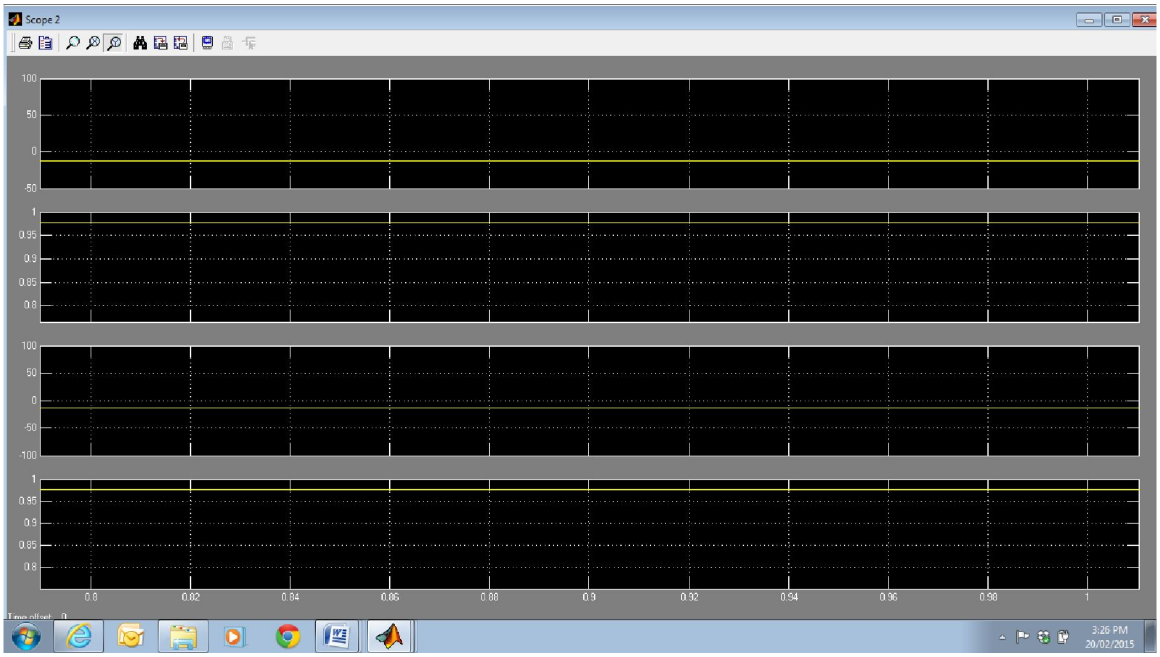

Figure 7: Displacement and power factor of fundamental current of rectifier and supply current

Refer scope 2 in fig. 1

Ch1: Fundamental current displacement for the load

Ch2: Power factor of Ch1 current

Ch3: fundamental current displacement of supply current

Ch4: Power factor of Ch3 current

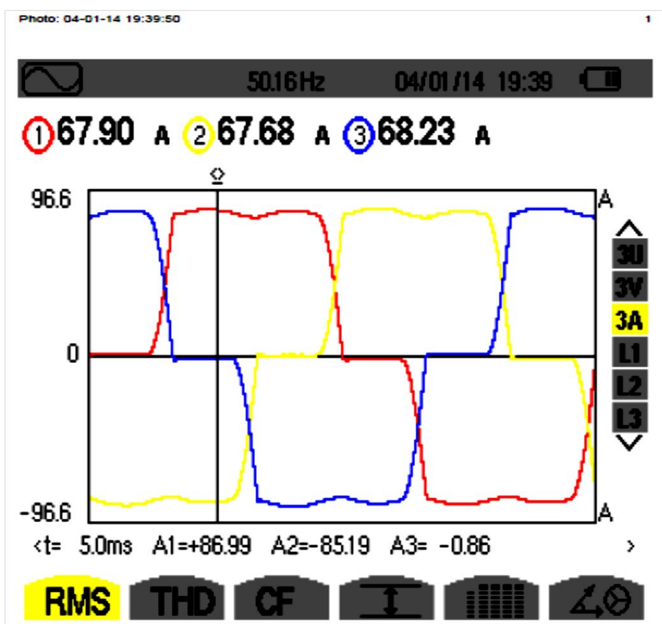

Figure 8: Rectifier input line currents

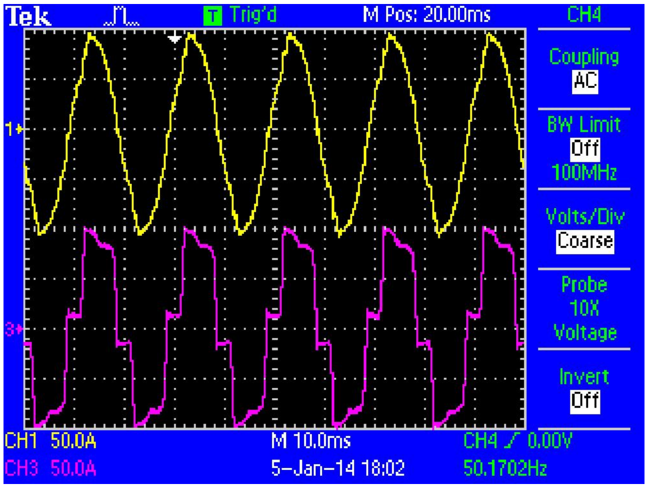

Figure 9: Supply current and rectifier current with more number of cycles

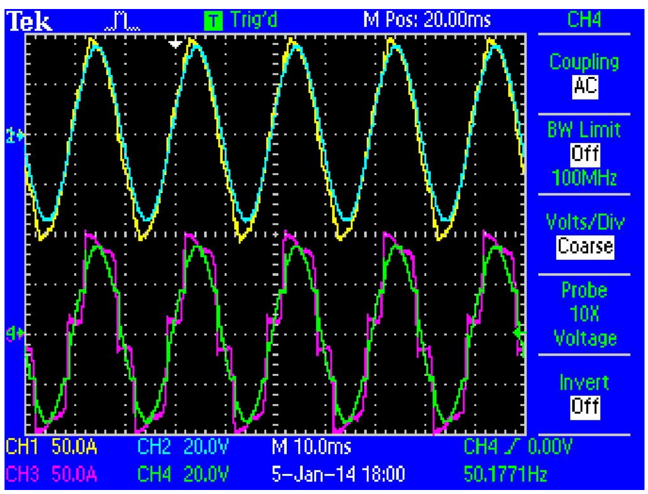

Figure 10: Supply voltage with supply line current and rectifier voltage and rectifier input current

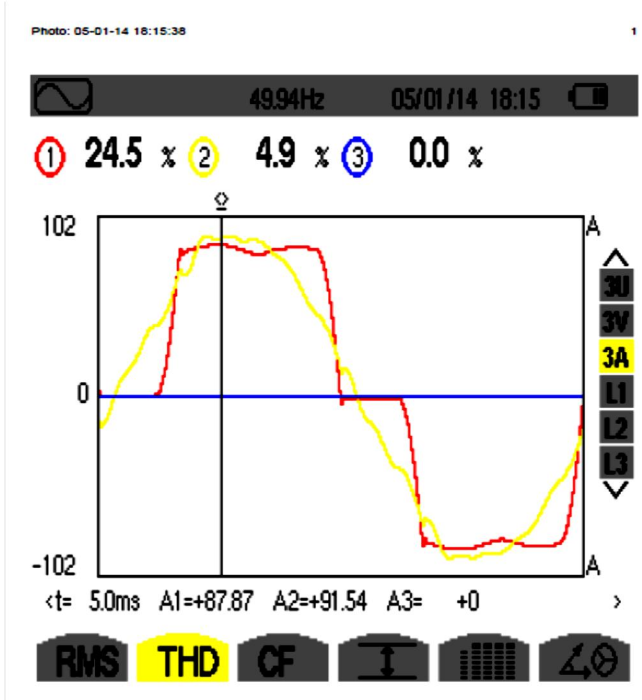

Figure 11: Rectifier input current and corresponding supply line current along with distortion indicated as 24.5% and 4.9% respectively

Figure 12: Experimental set up for testing

Figure 13: 12.24 mF, 45 A low voltage AC capacitor specifically developed for experimental verification and as required by the filter design