International Journal of Engineering & Technology, 7 (4.41) (2018) 24-30

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Performance Based Economical Design of Hybrid Filter and APFC to Improve the Power Quality of Industry

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Abstract

The aim of this paper to analyze the power quality (PQ) and provide a cost effective solution to mitigate the harmonics and improve the power factor (PF) in industry. The detailed harmonic analysis and monitoring performed to rectify the PQ issues. In this paper automatic power factor correction (APFC) for power factor improvement and hybrid power filter (HPF)which is combination of (APF) and passive Power filter (PPF) has been proposed. The design of active filter by two different control scheme has been proposed and compared. The modelling and simulation has been carried out to verify proposed analysis in MATLAB Simulink environment individually. To make the proposed solution cost-effective, combination of PPF only for fifth harmonic frequency and APF for other remaining harmonic frequencies has been used. The HPF reduces the cost as well as rating of the APF. The cost and rating of APF is also compared with and without passive filter of the system.

Keywords: *Automatic power factor correction; Active power filter; harmonics; hybrid power filter; Power quality; power factor; passive power filters.*

1. Introduction

The abundant use of nonlinear loads in industries as well as in small factories such as variable frequency drives and power converters etc. the power quality become worse [1]. The current harmonic distortion produces extra heat in the equipment's, increase the temperature of transformer, increase the size of neutral by overloading, overstressing of capacitors and nuisance tripping of circuit breaker [2,3]. To improve the quality of power it is essential to implement suitable harmonic mitigation techniques which is correspondingly cost-effective [4,5]. Methods for harmonic mitigation are classified as passive, active and multi-pulse rectifier techniques [6]. Some PPF techniques are still favored choices like ac and dc chokes in low power industrial applications [7,8]. The passive methods used due to their low cost, design simplicity, reliability and low maintenance. The other preferences are active methods, the shunt active power filters (SAPF) extensively used for compensation of harmonics and reactive power [9,10]. The effectiveness of SAPF is depend on how quickly and accurately harmonic compensation of nonlinear loads are identified [11,12]. The size and rating of APF is directly proportional to the current. When APF designed for enormous harmonic currents then its size and rating become a problematic to consumer as well as for manufacturer, as it increases the total cost. To reduce the cost, size and rating of APF, the combination of passive and active filters are used. The combination of active and passive filters are termed as Hybrid filters(HF)[13,14]. The hybrid filter is superior choice than APF. Usually the passive filters used for selected tuned frequencies and APF compensate all other harmonic currents. The passive filters generally considered for highest dominating frequency and for other frequencies, APF is good choice.

2. Problem Definition

As this industry has exceeded THD limit as per IEEE 519 standard, the actual current harmonics distortions were measured, I_R=13% I_Y=11%, I_B=13%. It was required to take effective actions to control current harmonics less than 5%. The dominant harmonics are 5^{th} and $7^{th}$with the harmonics current of 8% and 6% of fundamental current. In this industry two distinct problems are present, a very badly designed APFC panel and current harmonics due to nonlinear loads. This APFC panel amplifies the harmonicsabove the recommended level. The single line diagram of an industry has been shown in fig.1. Electricity Board sanctions the maximum demand of 411 KVA to this industry. The short circuit current (I_{sc}) is 8 KA and maximum demand load current (I_L) is taken by load is0.548 KA and the. The short circuit ratio (I_{sc}/I_L) is 14.54 and it is less than 20, so the maximum total demand distortion (TDD) allowed is 5%.

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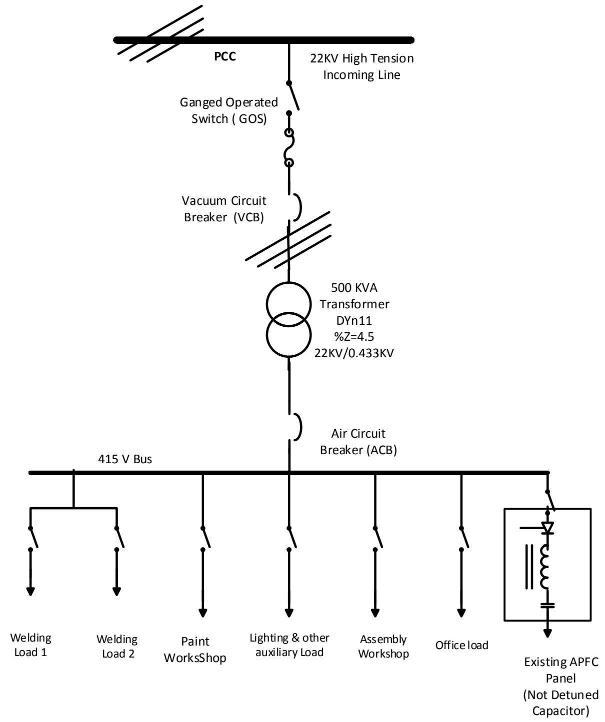

Fig. 1: Load distribution in industry

To determining the source of harmonics, a detailed harmonic analysis was carried out. The measured predominating harmonics are 5thand 7thorder. The main cause of harmonics and deterioration of power factor were found at two levels,

1. Harmonics amplification by existing APFC panel, which reduces the power factor
2. Production of harmonics by nonlinear loads.

2.1. Power Quality Parameter measurements

All theresultsof parameters related to PQ analysis has been shown from fig.2 to fig.6. All measurements were taken with and without APFC during 01:40 PM to 01:50 PM

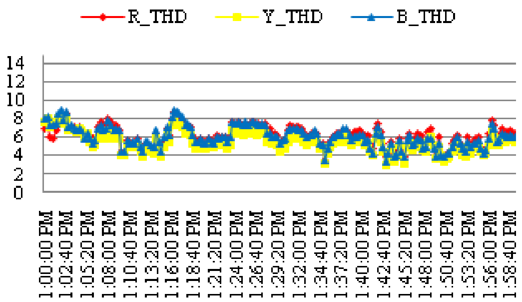

Fig. 2: Main current harmonic distortion

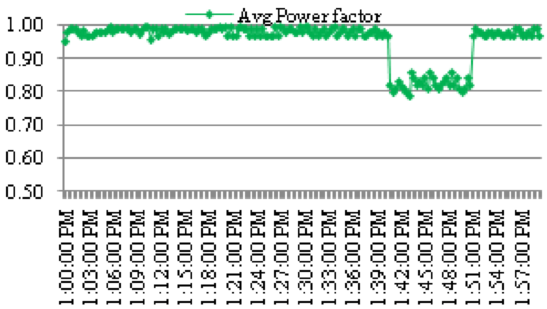

Fig. 3: Power factor variation

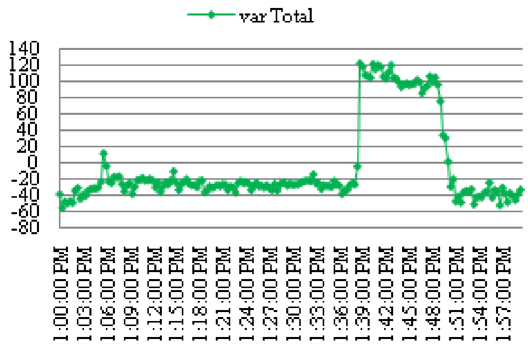

Fig. 4: Reactive power requirement

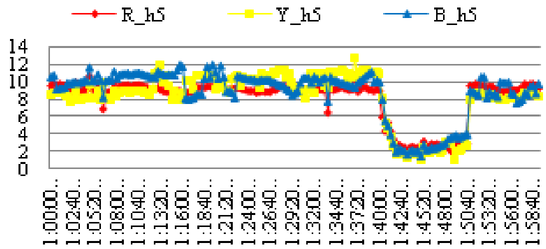

Fig. 5: Fifth harmonic current distortion

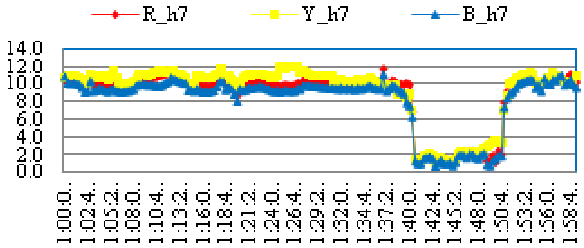

Fig. 6: Seventh harmonic current distortion

3. Designing of Proposed Scheme

The proposed scheme has combination of APF and PPF for harmonic mitigation and APFC for power factor correction.

3.1. Design of APFC

The proposed APFC panel having 7 steps for 210 KVAr panel as shown in fig. 7. To manage a magnetizing current of transformer, a 20 KVAr capacitor bank always kept connected and fixed. In this design, switching of capacitors at ‘zero’ current cross over level by using thyristor. If switching of capacitor at zero cross over then no initial in-rush current taken by capacitors. This process increases life and permits capacitors to be switched ON even under charged condition.

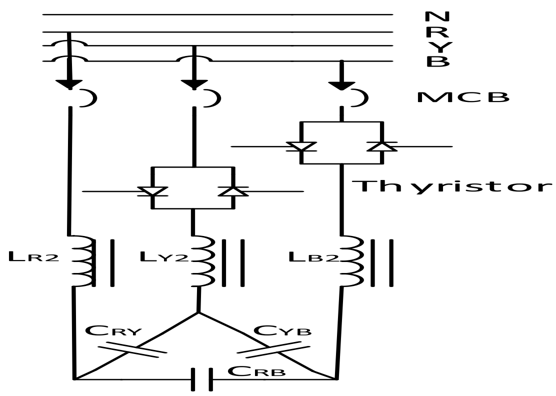

Fig.7: Proposed APFC Panel.

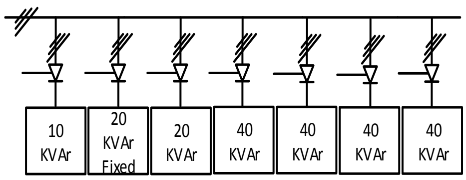

Fig. 8: APFC Panel of 210 KVAr with 7-step

In this case, harmonics of 5th and above order are present, so inductors of 7% are used for detuning of the capacitor. When detuning of capacitor is not done then it will draw more harmonic current. Due to drawing of more harmonic current, capacitor become overloaded and fail. In some condition, the capacitors also start resonating with the load inductance, which results in amplification of existing harmonics.

3.2. Design of Passive filters

It is necessary to design a passive filter, which should be able to take harmonic as well as fundamental current loading. The harmonic current (I_{hn}) always has two paths towards source and in tuned filter. The proposed design of PPF and its equivalent circuit as shown in fig.9. Here $Z_s$and I_s are impedance and current of source while Z_{fl} and I_{fl} are impedance and current of filter. For effective filtration, the value of Z_{fl} is kept as minimum as possible for harmonic frequency current and maximum for fundamental current. The passive filter is designed for 5th order harmonic current of 8% of fundamental current.

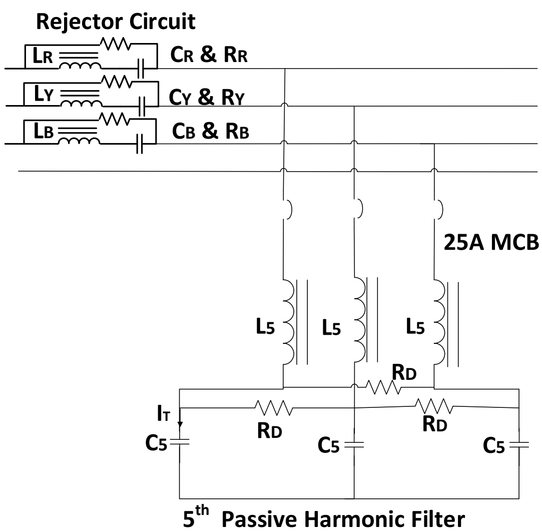

Fig. 9: Passive filter with rejector circuit

The reactive power is define as[5],

$X_c = V_{rc} / Q_c$ (1)

Where, V_{rc} is the nominal voltage of capacitor and Q_c is supplied reactive power.The capacitance of filter is define as

$C_F = 1/2 \pi f_s X_c$ (2)

Where, f_s is fundamental frequency. The value of inductance is define as
$L_F = 1/(2 \pi f_s)^2 (h_n)^2 C_F$(3)

The filter resistance (R) value is associated with quality factor (Q), which indicates the sharpness at the resonance. TheQ-factor is define as$Q=X_n/R$.

3.2.1. Design of Rejector Circuit

To obtain effective filtering for long time then filter impedance always be around one-tenth of the source side impedance. To make higher value of source impedance than filter impedance, rating of 6 mH inductor and of 1700 μF capacitors have been connected in series with the source. This type of LC series combination is act as rejector circuit for harmonic current. This combination provides resonance with source at the fundamental frequency and gives high impedance at other frequencies. Due to resonance with the fundamental frequency, no extra voltage drop is occurs. This rejecter circuit always keep impedance of source is higher than filter impedance. So always major part of harmonic current goes into the PPF not towards the source.

3.3. Design of Active power Filter

The design of an APF mainly comprises the design of the voltage source converter (VSC) to generate required compensating current by using suitable control scheme of switching and an interfacing inductor, which reduces the ripples present in a compensating current. The VSC design includes DC capacitance, the level of DC bus voltage, and voltage and current ratings of IGBTs.

3.3.1.DC bus Voltage

For a three phase VSC, the DC bus voltage can be given as:

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}\ m} \quad (4)$$

Where, modulation index (m) considered as 0.9and V_{LL} is 415 V. The calculated V_{DC} is690.19≈ 700 V

3.3.2. DC Bus capacitor

The DC bus capacitor value calculated as

$$0.5C_{DC}[(V_{DC}^2 - V_{DC1}^2)] = 3V_{ph}k(aI_h)t \quad (5)$$

Where, V_{DC1} is 690 V, V_{ph} and I_h is phase voltage and harmonic current of 240 V and 50 A respectively. Here k is safety factor taken as 0.1 and t is time by which DC bus voltage is to be recovered is 60 ms and a is overloading factor and taken as 1.2.

The calculated $C_{DC}$is 16784.60 μF and selected value is 17000 μF

3.3.3.AC Inductor

The value of inductance mainly based on the ripple current (I_{crpp}). This current is usually 25% more than $I_{hn}$and f_s is 10kHz.

$$L_f = \frac{\sqrt{3}\ mV_{DC}}{12\ a\ f_s I_{crpp}} \quad (6)$$

The L_f is calculated as 0.67 mH and selected value is 0.8 mH.

3.3.4. Voltage rating of IGBTs

$V_{sw} = V_{DC} + V_d$ (7)

Where, V_d is 10 % overshoot in dynamic conditions, the voltage rating is 770 V with safety factor it is 1200V.

3.3.5. Current rating of IGBTs

$$I_{sw} = 1.25(I_{cr} + I_{sp}) \quad (8)$$

Where I_{sp} and I_{cr} are the peak value and ripple current of APF current is 200 A.

For the control of APF, the major task is to derive a reference current and thereafter generating switching or gating pulse for VSC switches by using a proper current controller.

4. Simulation of Hybrid Filter

In this case, APF is simulated and designed with two controlled scheme and then compared for performance. The control block is first simulated using IRP theory and then SRF theory. For reducing the size and rating of APF, a passive filter is also coupled in shunt to the APF. For validation of hybrid filter in simulation, a three-phase circuit breaker is used to provide the flexibility to switch on/off any of the filters according to requirement.

4.1 Simulation Results

When no compensation is done, the source current was distorted and THD of 24% as shown in figure 10.

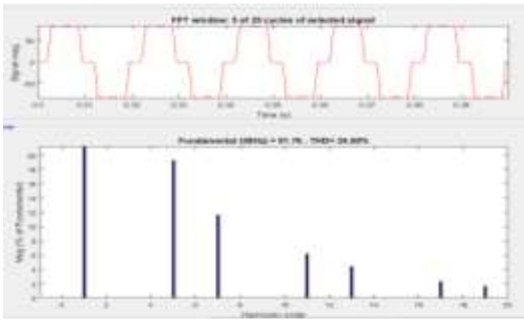

Fig. 10: FFT analysis without any filter

The figure 11 and 12 shows the IPRT control scheme and fig, 13 and 14 shows the SRF control scheme results.

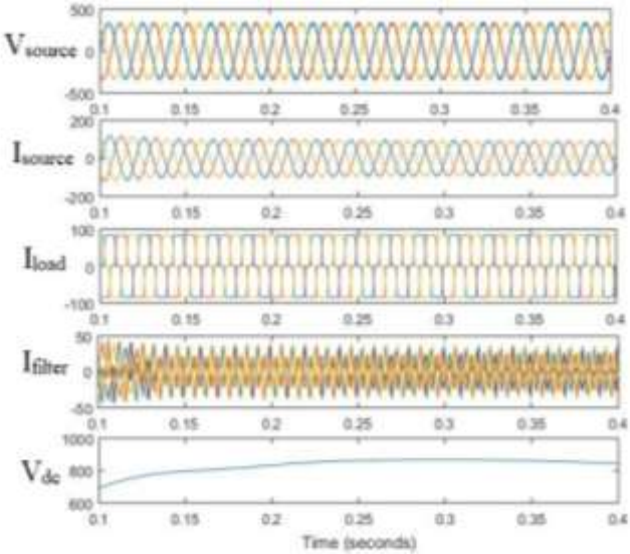

Fig. 11: APF with IRPT Control Scheme

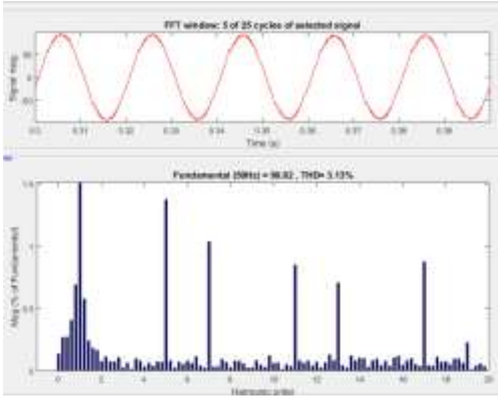

Fig. 12: FFT Analysis of APF with IRPT control scheme

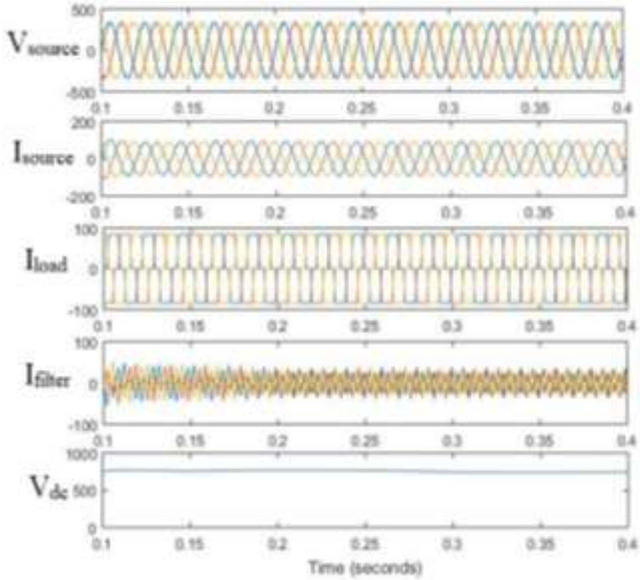

Fig. 13: APF with SRF control Scheme

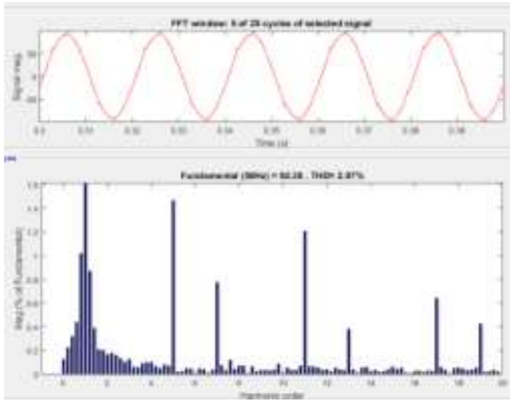

Fig. 14: FFT analysis of APF with SRF control scheme

When passive filter added to the IRPT control scheme, the results as shown in fig. 15 and 16.

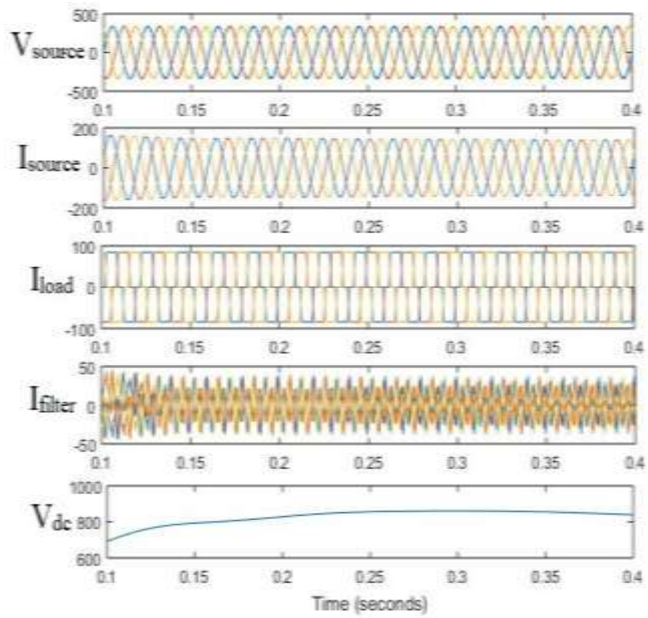

Fig. 15: PPF and APF with IRPT control scheme

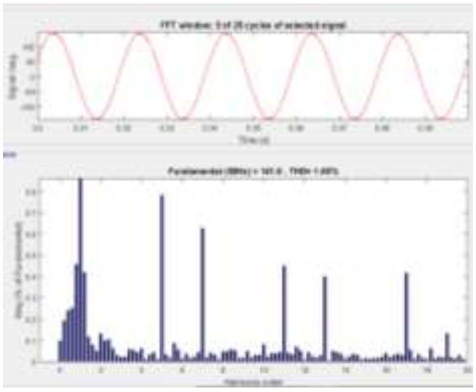

Fig. 16: FFT analysis of PPF and APF with IRPT control scheme

When passive filter added to, the SRF control scheme results as shown in fig. 17 and 18.

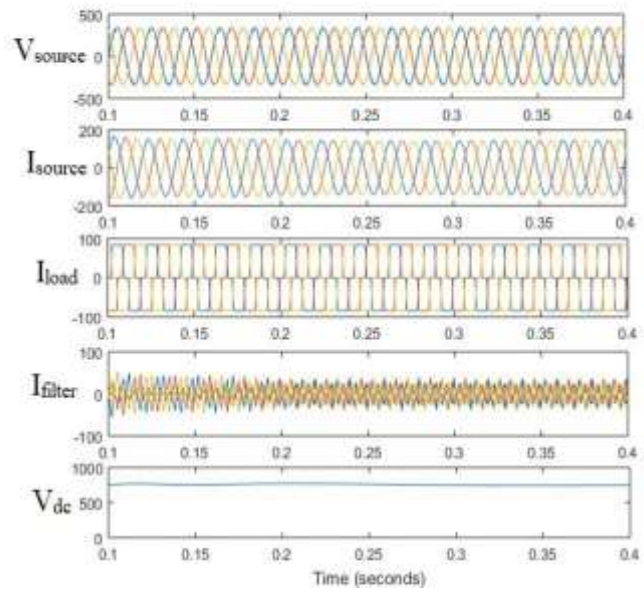

Fig. 17: PPF and APF with SRF control Scheme

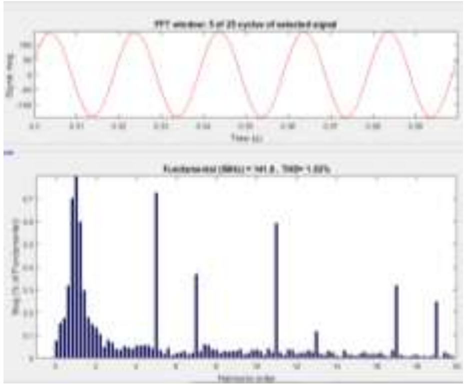

Fig. 18: FFT analysis of PPF and APF with SRF control Scheme

5. Proposd Scheme and Hardware Results

The proposed solution is consist of APF, PPF with rejector circuit and detuned APFC panel. This solution enhances the reliability and decrease the cost of the system as shown in fig. 19.

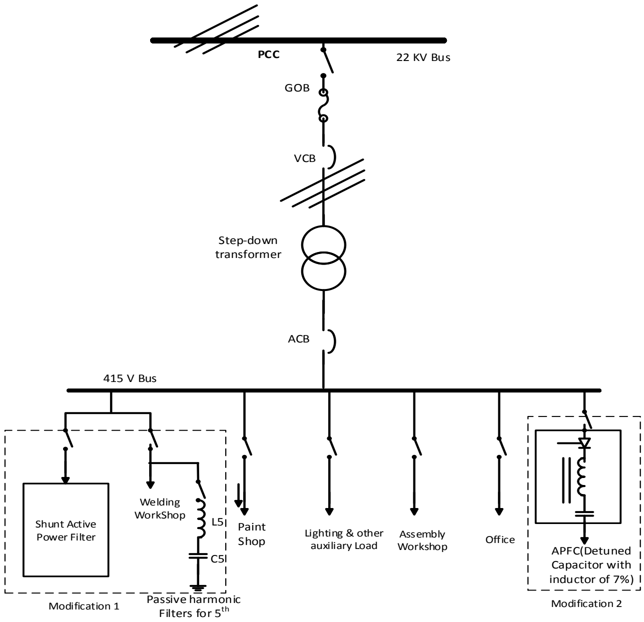

Fig. 19: Proposed solution in industry

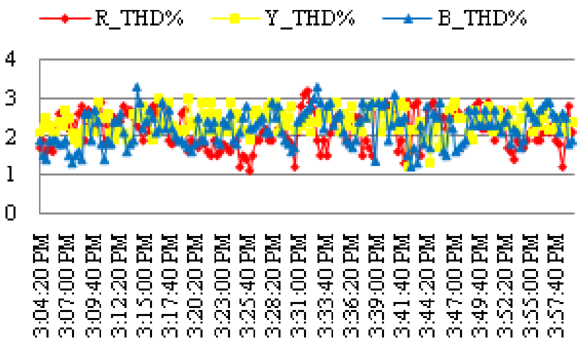

Fig. 20: Main current harmonic distortion

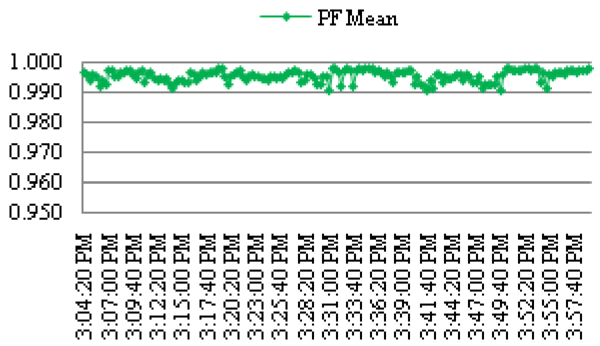

Fig. 21: Power factor in main line

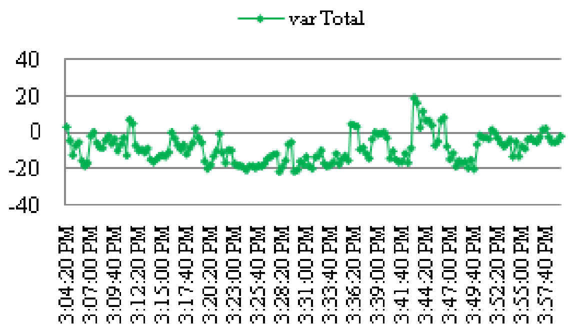

Fig.22: Reactive Power

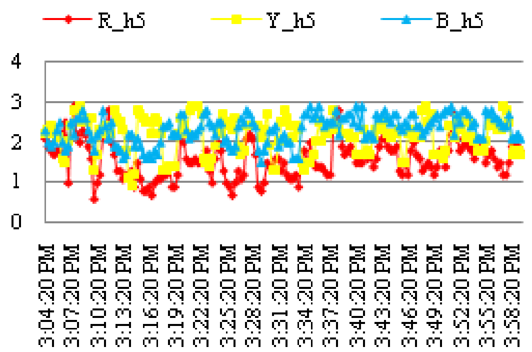

Fig. 23: Fifth harmonic current distortion

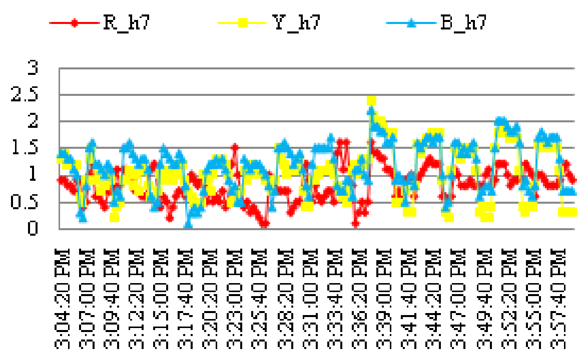

Fig. 24: Seventh harmonic current distortion

The ratings of selected component is shown in table 1 and their comparison in terms of THD compensation and working performance has been shown in table 2 and 3.

Table 1: Specification of Selected Component

	Component	Rating
1	**APFC**	210 kVAr
	Inductor (L_{R2}, L_{Y2}, L_{B2})	7%, 3-Phase
	Capacitor (C_{RY}, C_{YB}, C_{BR})	(10, 20,25) kVAr, 525V
2	**PPF**	
	Inductor (L_5)	8.2 mH/25 Amp
	Capacitor (C_5)	50 µf, 450V, 1-Phase.
	Resistor(R_D, R_D, R_D)	100 K
	Switched fuse Unit (SFU)	100A
	REJECTOR	
	Inductor (L_R, L_Y, L_B)	6 mH, 60 A
	Capacitor (C_R, C_Y, C_B)	1700 µF
	Resistor(R_R, R_Y, R_B)	40 K, 5 Watt
3	**APF**	415 V, 50A

Table 2: Comparison of IRPT and SRF Control Scheme

	IRP Theory THD %	**SRF Theory THD%**
No filter is connected	24.00 %	24.00 %
Only PPF is connected	15.16 %	15.16 %
Only APF is connected	3.13 %	2.97 %
Both APF and PPF is connected	1.65 %	1.53 %

Table 3: Performance Comparison of IRPT and SRF Control Scheme

	IRP Theory	**SRF Theory**
Harmonic mitigation	Good	Better
Reactive power Compensation	Average	Good
Load balancing	Good	Average
Complexity	High	Average

6. Economic Aspects

In this paper, comparison has been made on the basis of cost and performance. The installation and maintenance cost has been excluded because it vary from project to project and manufacturer to manufacturer. All the specifications of APFC, APF and PPF as shown in Table 4.

Table 4: Ratings of APF with and Without PPF

Only active filter is connected (for 70A)	51 kVA
Both active and passive filters are connected (for 50A)	36 kVA

Table 5: Cost Comparison

	Mitigation Technique	Cost ($)
i	APFC (Thyristor Controlled)	4091.72
ii	Shunt passive filter (only for 5^{th})	1000
ii	Active harmonic filter (alone for 70A)	4929.49
iii	Active harmonic filter with PPF (50A)	3271.23

7. Conclusion

The power quality analysis has been carried out in an industry where major connected loads are nonlinear and fast variable nonlinear. These loads produces harmonic pollution above the recommended level and existing APFC panel amplifies the harmonics. As per the demand, various active, passive and hybrid techniques are used for PQ improvements. The design of active filter with two different control schemes along with the designing of a shunt connected passive filter successfully carried out. MATLAB Simulink environment is used to carry out the simulation. All results presented and discussed in detail to validate the performance of both the filters. All the values of THDs are within prescribed limit according to IEEE 519 standard. It can also be concluded that performance of active filter with SRF control theory is better than with IRP control theory in mitigating harmonics. The active filter along with the shunt passive filter is capable of further reducing the THD from source current and hence enhancing its performance. The rating, size and cost of the active filter are reduced by employing a passive filter in shunt from 51 kVA to 36 kVA. PPF is designed to divert the dominant 5thharmoniccurrent from the system. The proposed solution is consist of APF, PPF with rejector circuit and detuned APFC panel. In APFC panel, an inductor of 7% is detuned with capacitor which leads to better performance in terms of power factor and does not amplify any harmonics. This solution is economical and reliable in operation. The aim of this paper is to achieve target i.e. improved power factor near to 0.98and reduction in TDD below 5% with cost effectiveness. As per the present market trend, only APF are at least 20% -30% costlier than hybrid type filter solution.

Acknowledgement

The authors acknowledge the support rendered by **A.S.Tare** from **UDEET ELECTRICALS**, a Manufacturing Company for PQ solutions in Dombivli (Mumbai), Maharashtra for carrying out this work. The authors also sincerely thank him for his technical support throughout the period for preparing this paper.

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