Harmonics Suppression in Distribution Networks composed of Uninterruptible Power Supply Systems

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***Abstract*—In recent years, utilization of power electronic converters has been drastically increased. These converters act like non-linear loads for utility grid. Such non-linear loads distort the supply current through injection of harmonics. One such example is the uninterruptible power supply (UPS) system, which is a major source of current harmonics. These harmonics affect the performance of distribution transformers in terms of losses, heating of core, stress on insulation and tripping of the protection relays. In this paper, the increase of total harmonic distortion (THD) of the supply current, caused by uncontrolled rectifiers used in UPS systems, has been minimized. Two methods including passive filters (PF) and active filters (AF) have been applied to minimize the THD. The simulations have been performed in MATLAB/Simulink environment where the results of both schemes have been compared under various load conditions (RL and unbalanced load). It has been found that AF provides a better solution as compared to PF for such load conditions.**

Keywords— Harmonics, Total Harmonic Distortion, Power quality, Passive filters, active filters, distribution network

I. INTRODUCTION

The infiltration of power electronics based devices into the utility grid has given rise to power quality problems. Power quality refers to pure sinusoidal waveform of voltage and current [1-3]. In many developing countries, due to shortage of the generation capacity, the usage of uninterruptible power supply (UPS) systems has gained popularity. These UPS systems are mostly low priced and are based on uncontrolled rectifiers. These rectifiers act like non-linear loads and draw non-sinusoidal current from the utility grid. As a result, harmonics are injected into the utility grid and total harmonic distortion (THD) of supply current is increased. This distorted current causes the overheating of transformer winding, stress on insulation and excessive tripping of protection relays/circuit breakers [4-5].

Harmonic current is specified by a frequency which is an integral multiple of the fundamental frequency (normally 50Hz). Harmonics may produce in an infinite order and occur in positive, negative and zero sequence. In the domain of power system, harmonics are categorized as odd, even and triplen harmonics [6]. In distribution networks, the harmonic current effects the transformer performance in three ways [7-8], due to harmonic injection, the amount of power needed exceeds the rated power (kVA) of transformer, higher harmonics increase the current magnitude which results in excessive copper loss, and high harmonics also cause an increase in eddy currents which eventually rise the core temperature and stress the insulation.

The worldwide standards regarding power quality of electricity (EN-50160, IEC-61000, and IEEE-519) impose that electrical apparatus and services should generate harmonics within identified limits. Furthermore, these standards also identify the supply voltage distortion limits. [9]. It is mandatory to resolve the distortion problems produced by nonlinear loads. For this purpose, filters are used in electrical system to limit the harmonics within specified limits [10]. Generally, filters are categorized into two major types, i.e. passive filters (PFs) and active filters (AFs). PFs involve the combinations of capacitors and inductors to offer a low impedance path to distorted currents. It only permits the fundamental current to flow in the distribution network. Passive filters are generally classified on the basis of frequency elimination and are classified into four types [11]. Low pass filters (LPF), Fig 1 (a), only allow lower frequencies to pass, while blocking all other higher frequencies.

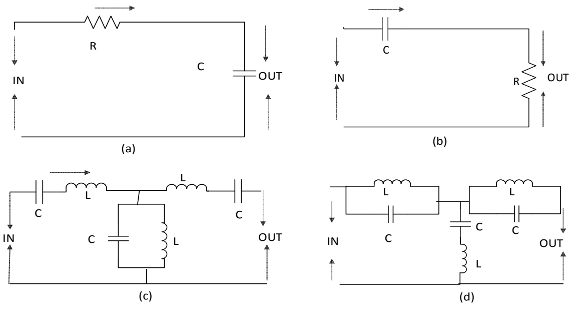

Fig.1. Passive filter (a) LPF (b) HPF (c) BPF (d) BSF

It consists of series combination of resistors and capacitors. The filtration depends upon the values of capacitors and resistors. High pass filters (HPF), Fig 1 (b), block lower frequencies, while allowing higher frequencies to pass. It also consists of series combination of capacitors and resistors, connected in reverse order of LPF. Band pass filters (BPF), Fig 1 (c), only permit a specified band of frequencies to pass. On the other hand, band stop filters (BSF), Fig 1 (d), block specific frequencies, while allowing other frequencies to pass [12-13].

For a specific harmonic elimination, the PFs are further classified into single tuned; double tuned and double tuned C-type filters. A single tuned filter is a series RLC circuit tuned for a single harmonic as shown in Fig 2. The capacitor and inductor are chosen in such a manner that the branch impedance is zero near the harmonic frequency in order to bypass that harmonic. This filter is based on three design parameters which are harmonic current order, capacitive reactive power and its quality factor (Q). In addition, the network's voltage level and fundamental frequency must also be considered during the design process. A resistor could be used to adjust the sharpness of tuning [14].

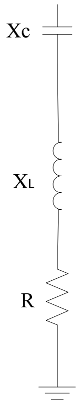

Fig.2. Single tuned filter

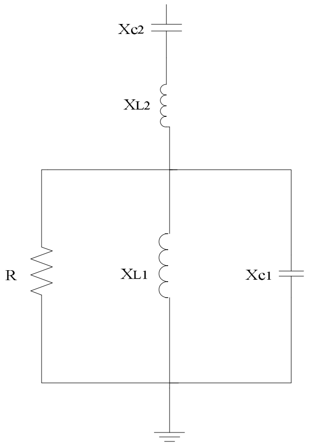

Fig.3. Double tuned filter

The parameter '*Q'* is the bandwidth of the filter and is defined as the ratio between the reactance (*X*) and the resistance (*R*). A typical range for *Q* is between 30 and 60.

$$C = \frac{Q_c}{2\pi f V^2} \tag{1}$$

$$X = \frac{1}{2\pi f h C V^2} = \sqrt{\frac{L}{C}} \tag{2}$$

$$L = \frac{X}{2hf} \tag{3}$$

$$Q = \frac{2hfL}{R} \tag{4}$$

$$R = \frac{1}{2\pi f C} \tag{5}$$

Inductive reactance (*X*) depends on C, the capacitance, harmonic order (h), reactive power (Q_c), quality factor (*Q)*, network frequency (f) in Hz, and the network voltage (*V)* in volts.

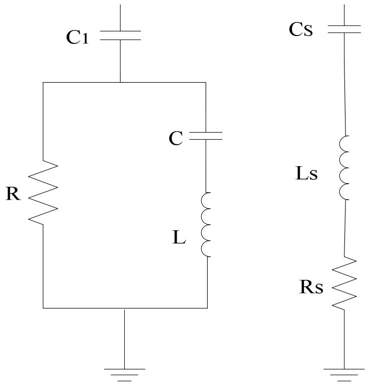

Fig.4. Double tuned C-type filter

A double tuned filter, as shown in Fig 3 and double tuned C-type filter shown in Fig 4. It is a combination of BF in series with an inductor (L_2) and capacitor (C_2). This filter works by combining the parallel resonance of the BF with the series resonance of *LC*. Double tuned C-type filters are 2nd order filters having the capacity of suppressing harmonics with lesser losses. It is because of the parallel combination of *R* with *LC* circuit. C-type filters function very well in order to suppress high frequency harmonics as they offer flat impedance characteristic. The following equations are used to design a C-type double tuned filter [15].

$$Z(W) = \left(\frac{1}{R} + \frac{1}{jWL - j(WC)^{-1}}\right)^{-1} + \frac{1}{jWC_1} \tag{6}$$

$$Z(W) = \left(\frac{R\times(W^2LC-1)^2 + jR^2WC\times(W^2LC-1)}{(RWC)^2 + (W^2LC-1)^2}\right) - j\frac{1}{WC_1} \tag{7}$$

$$L_s = L = \frac{V^2}{2\pi f Q_c (h_o^2 - 1)} \tag{8}$$

$$C_s = \frac{Q_c (h^2 - 1)}{2\pi f h^2 V^2} \tag{9}$$

$$C = \frac{Q_c(h^2-1)}{2\pi fhV^2} \tag{10}$$

$$\frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C} \tag{11}$$

$$R = \frac{QV^2}{hQ_c} \tag{12}$$

AFs were developed in 1983 and are based on instantaneous power theory [16]. AFs are matured with advancements in control theory and semiconductor switches [17]. SAPFs work as a voltage source converter (VSC) and cancels out load harmonics by injecting anti-harmonics of same magnitude but opposite polarity [18], as shown in Fig 5.

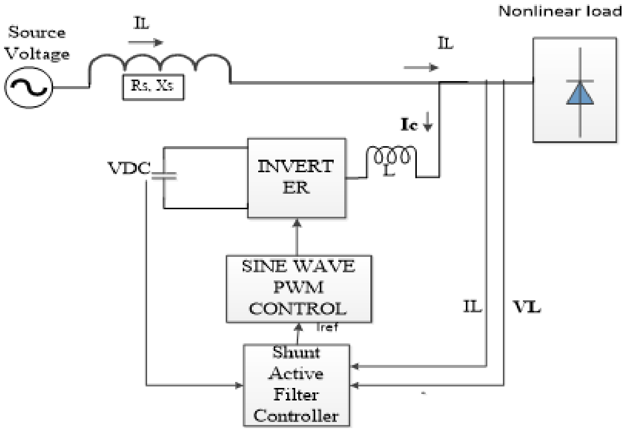

Fig.5. Schematic diagram of AF control

II. SIMULATION MODEL

A distribution network supplied by three-phase, 11kV/400V, 50Hz with UPS (three-phase bridge rectifiers) as non-linear load is simulated to consider the effect of harmonics, as shown in Fig 6. The detailed parameters are listed in Table I. The UPS is further loaded with *RL* and unbalanced loads. The same network is simulated with PFs and AFs to investigate the performance of filters.

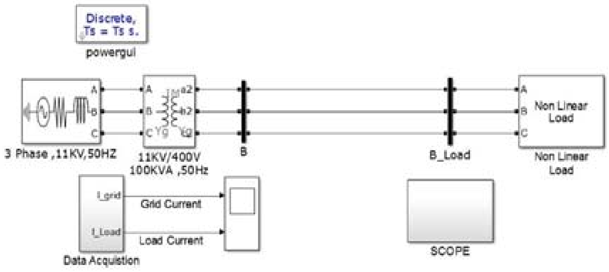

Fig.6. Simulation model of distribution system with nonlinear load

A. Simulation Model with PFs

As a first case, four PFs are connected in parallel between UPS and distribution transformer. These PFs will mitigate 5th, 7th, 11th, 13th, 17th and 19th harmonics, as shown in Fig 7.

TABLE I. DETAILED SIMULATION PARAMETERS

No.	Component	Parameter
1	Grid Voltage	11kV
2	Distribution Transformer Rating	100kVA
3	Distribution Transformer Voltage	11kV/400V
4	Source Resistance (R_s)	0.89Ω
5	Source Inductance (L_s)	16.85mH
6	Line Resistance (R_L)	0.4Ω/phase
7	Line Inductance (L_L)	3.55mH/phase
8	UPS Resistance (R_{UPS})	1mΩ
9	Snubber Resistance ($R_{snubber}$)	500Ω
10	Load Resistance (R_{load})	50Ω
11	Load Inductance (L_{load})	20mH
12	Unbalanced Load 1 (R_{phase1})	10Ω
13	Unbalanced Load 2 (R_{phase2})	20Ω
14	Unbalanced Load 3 (R_{phase3})	50Ω

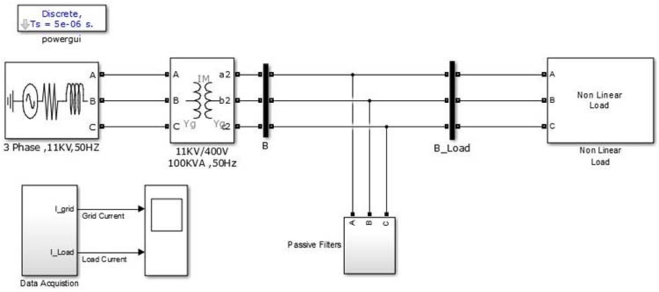

Fig.7. Simulation model of distribution system with PF

B. Simulation Model with AFs

As a second case, an AF is connected in parallel between UPS and distribution transformer, as shown in Fig 8.

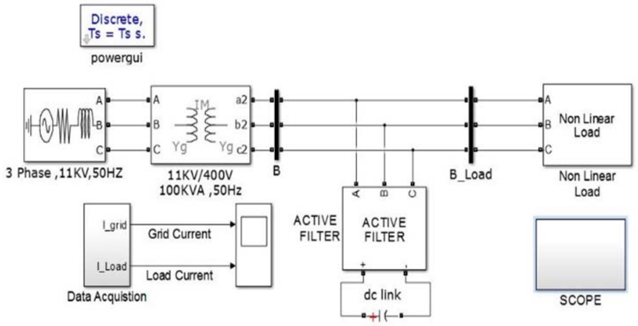

Fig.8. Simulation model of distribution system with AF

The AF observes the supply current i_{abc} and generates a current i_{abc}* of same magnitude but opposite polarity. The AF contains three core blocks, a power stage with a capacitor storage, a pulse width modulated (PWM) converter and a AF controller. By using a low pass filter, the current with higher harmonics is filtered out. An *abc* to *dq* transformation of supply voltage v_{abc} and current i_{abc} is carried out. As a result, the active power P and reactive power Q is calculated by using the following equations.

$$P = V_d * I_d \qquad (13)$$

$$Q = V_q * I_q \qquad (14)$$

By using equations (15) and (16), reference active power P^* and reactive power Q^* values are used to calculate i_d^* and i_q^*. To transfer pure active power P, the reference reactive power Q^* is set to zero. In this way i_d has to be controlled. While assigning a negative value to P^*, a negative id^* is obtained. This eventually results in a current i_{abc}^* which is of same value as i_{abc} but opposite in polarity. This current is injected into the distribution network by using PWM converter. The PWM switching frequency is always kept 10 times higher than the highest frequency harmonic. The complete control scheme is shown in Fig 9.

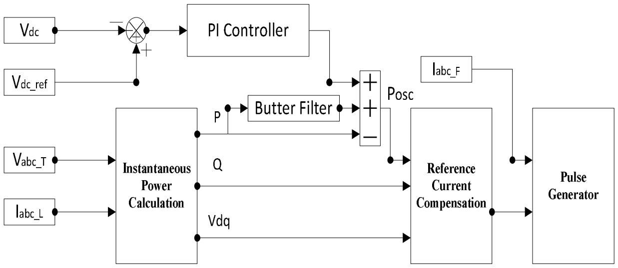

Fig.9. Control scheme of AF

$$I_d^* = \frac{P^* * V_d + Q^* * V_q^2}{V_d^2 + V_q^2} \qquad (15)$$

$$I_q^* = \frac{P^* * V_d - Q^* * V_q^2}{V_d^2 + V_q^2} \qquad (16)$$

III. SIMULATION RESULTS

From load perspective, two test cases have been considered. For case-I, the UPS with an RL load is considered. Similarly, for case-II, the UPS with unbalanced load is considered. Both filtration techniques PFs and AFs are applied to test cases and results are investigated.

a) RL Load (Case-I)

An *RL* load of 50Ω and 20mH is connected to UPS. It is observed that initial THD of supply current is 24.74%, as shown in Fig 10. At 0.1 sec PFs are applied to mitigate the harmonics. It is observed that THD of supply current reduces to 3.84%, as shown in Fig 11. The current waveform is shown in Fig 12. Similarly, at 0.1 sec AF is applied to mitigate the harmonics. It is observed that THD of supply current further reduces to 1.93% as shown in Fig 13. The current waveforms are shown in Fig 14 and Fig 15.

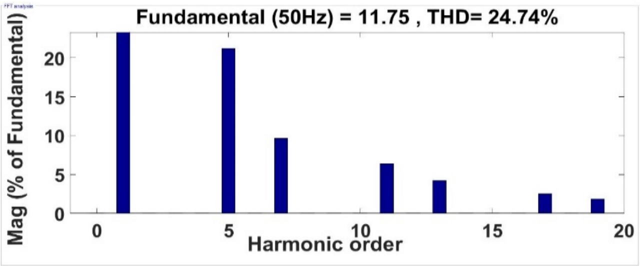

Fig.10. THD with *RL* load without filter

b) Unbalanced Load (Case-II)

An unbalanced load of 10Ω, 20Ω and 50Ω is connected to UPS. It is observed that initial THD of supply current is 14.81%, as shown in Fig 16. At 0.1 sec PFs are applied to mitigate the harmonics. It is also observed that THD of supply current reduces to 3.11% as shown in Fig 17. The current waveform is shown in Fig 18. Similarly, at 0.1 sec AF is applied to mitigate the harmonics. It is further observed that THD of supply current further reduces to 2.16% as shown in Fig 19. The current waveform is shown in Fig 20.

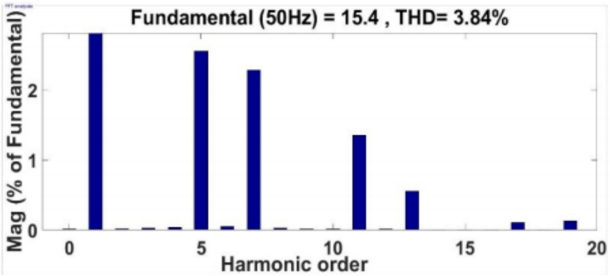

Fig.11. THD with *RL* load with PF

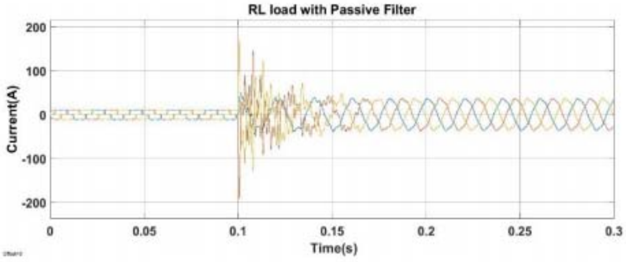

Fig. 12. Current compensation in *RL* load with PF

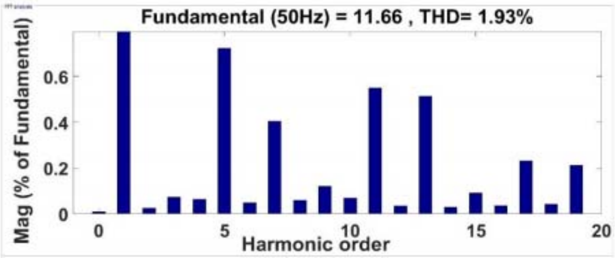

Fig.13. THD with *RL* load with AF

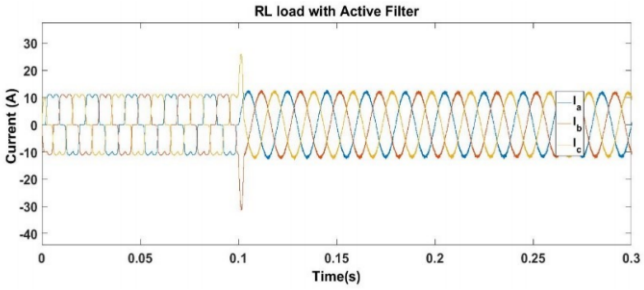

Fig. 14. Current compensation in *RL* load with AF

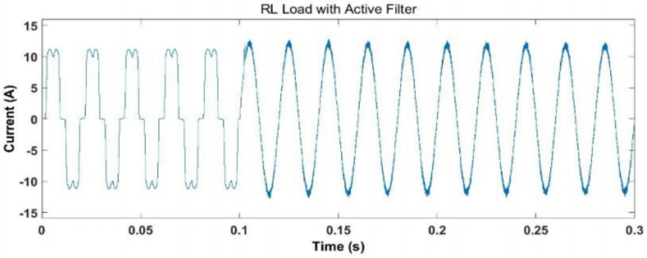

Fig. 15. Per phase current compensation in *RL* load with AF

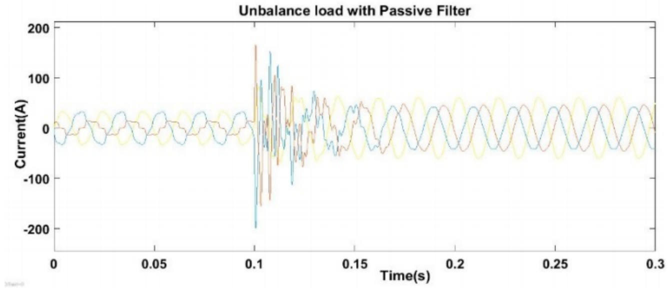

Fig. 16. Current compensation in unbalanced load with PF

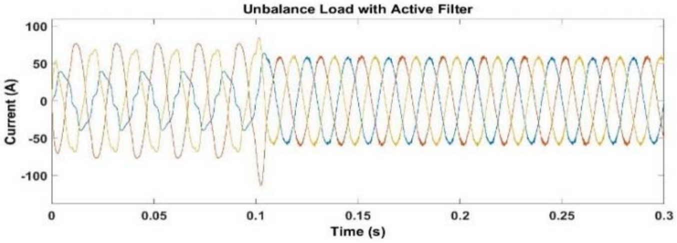

Fig. 17. Current compensation in unbalance load with AF

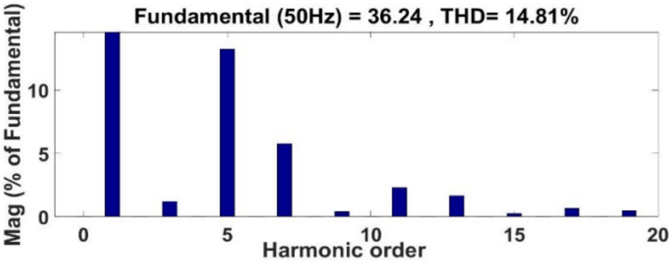

Fig. 18. THD with unbalanced load without filter

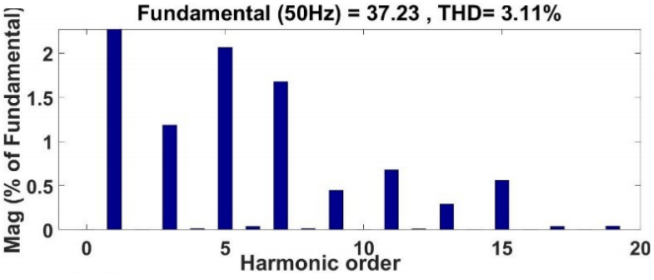

Fig.19. THD with unbalanced load with PF

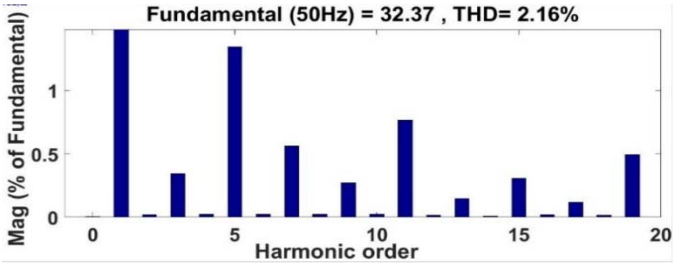

Fig. 20. THD with unbalanced load with AF

IV. ANALYSIS

The numerical values from above test cases have been compared and are shown in following Tables. Table II shows the magnitudes of most dominant current harmonics due to *RL* and unbalanced loads. It is clear that 5th, 7th, 9th, 11th, 13th, 17th and 19th are dominant harmonics. Table III shows the suppression of these harmonics with PFs. Similarly, Table IV shows the suppression of these harmonics with AF. Table V shows the THD of supply current without and with filters. It is clear that AF outperforms the PFs in terms of harmonic 0suppression.

Table II. % THD without filters

Load types	$H_5\%$	$H_7\%$	$H_9\%$	$H_{11}\%$	$H_{13}\%$	$H_{17}\%$	$H_{19}\%$
RL load	21.17	9.62	00	6.4	4.19	2.49	1.83
Unbalance load	1.19	13.25	5.76	2.29	1.65	0.66	0.46

TABLE III. % THD WITH PASSIVE FILTERS

Load types	$H_5\%$	$H_7\%$	$H_9\%$	$H_{11}\%$	$H_{13}\%$	$H_{17}\%$	$H_{19}\%$
RL load	2.67	1.86	00	1.37	0.55	0.11	0.13
Unbalance load	2.17	1.45	0.44	0.65	0.29	0.04	0.04

TABLE IV. % THD WITH SAPF

Load types	$H_5\%$	$H_7\%$	$H_9\%$	$H_{11}\%$	$H_{13}\%$	$H_{17}\%$	$H_{19}\%$
RL load	2.17	1.45	0.44	0.56	0.95	0.04	0.04
Unbalance load	1.25	0.51	0.32	0.81	0.16	0.07	0.48

TABLE V. % THD COMPARISON OF GIRD SIDE CURRENT

Load type	Without Filter	With PF	With SAPF
RL load	24.74 %	3.84 %	1.93 %
Unbalance load	14.81 %	3.11 %	2.16 %

V. CONCLUSIONS

In this paper, a detailed simulation based analysis is done for the harmonics suppression in distribution networks composed of uninterruptable power supply systems (UPS). The principal objective of this study is to evaluate various techniques for improving the power quality in the distribution networks. It has been found that the THD of supply current due to the injection of harmonics by UPS (power converters) can be minimized by using conditioning electronics. Two methods passive filters (PF) and active filters (AF) are used to suppress the harmonics. It has been perceived that for each specific harmonics, separate passive filtering is required for every fundamental frequency. On the other side, a single active filter suppresses all harmonics. Moreover, the THD improvement by AF filter is better than PF. The peak value of supply current is also minimized by using active filtering. In future, a test bench setup is in development to demonstrate the real time power quality effects on smart grid performance and load management in power distribution networks.

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