Journal of Advanced Science and Engineering Research Vol 4, No 4 December (2014) 220-231

Mitigation of Harmonics by Filters and Appropriate Active Filter Sizing in the Heavily Polluted Low Voltage Distribution Networks

Article Info

Received: 18/ 8/2014
Accepted: 29/8/2014
Published online: 1/9/2014

Walid Helmy
Electrical Power and Machines Department Faculty of Engineering - Ain Shams University, Cairo, Egypt

helmy_walid@yahoo.com, whabdelwhab@kku.edu.sa

ISSN 2231-8844

Abstract
This research studies the effect of harmonic filters on the low voltage (LV) distribution networks. With the high penetration of nonlinear loads and capacitor bank for power factor correction, the total harmonic distortion (THD) is increasaed and aggravated to be beyond the allowable limit. The higher THD pollutes the distribution networks; also, it is considered one of the main origins of the power quality deterioration. With higher THD in voltage (THDv), the sensitive loads may be damaged and the network components may be subjected to severe thermal stresses. So, at certain level of the THDv, designers must take the decision to intervene harmonics filters to reduce the previous bad effects. Passive and active filters are traditional and novel technologies respectively, both are used to suppress the THD in the level of distribution networks. In this research, the proposed algorithm provides a comparison between the two types of filters and illustrates how to determine the proper size of the active filter (AF) to retain the allowable harmonic levels. HARENA and MATLAB programs are used to simulate the proposed algorithm and the obtained results show the AF superiority on the passive filters, also, the appropriate sizing of active filter reduces its module cost.

Keywords: Power Quality, Harmonic Analysis, Passive Filters, Active Filters, Capacitor Banks, Low voltage Switchboard

1. INTRODUCTION

With the widespread of implementing the modern technologies (electronics and micro-processor based) in the most industries, the harmonic distortions increase and helpless the dependability level in the distribution networks and deteriorate the power quality in that networks. Not only electronics and microprocessors generate harmonics but also the capacitor banks for power factor correction amplify that harmonics (Dugan et al., 1996). Harmonic currents and voltages are superimposed on the fundamental, thus, there will be collective effects on equipment and devices connected to the same distribution level in the network. The damaging effects of these harmonics depend on the type of load encountered, and these harmful effects are classified into (Collombet et al., 1999):

1.1 Instantaneous effects:

Harmonics in voltage can disturb controllers used in electronic systems; for example, it affects the thyristor switching conditions by shifting the zero-crossing of the voltage waveform (IEC 146 2, 2010; Calvas, 2012).

- Harmonics can cause additional errors in induction-disk electricity meters.
- The electro-dynamic forces produced by the harmonic currents cause vibrations and acoustical noise, especially in electromagnetic devices (transformers, reactors, etc.).
- Pulsating mechanical torque, due to harmonic rotating fields from harmonic current, can produce vibrations in rotating machines.
- Disturbances in communication or control circuits that run beside power distribution circuits carrying distorted currents due to harmonics.

1.2 Long-term effects:

- In addition to mechanical fatigue due to electro-dynamic forces, the main long-term effect of harmonics is heating of some distribution networks components like capacitors, transformers, rotating machines, and cables (Collombet et al., 1999).
- Capacitor heating: inside the capacitors, there are two phenomena cause losses and heating: conduction and dielectric hysteresis. As a first reason, they are proportional to the square of the effective current. Capacitors are therefore sensitive to overloads, whether due to an extremely high fundamental or to the existence of voltage harmonics. These losses are defined by the dielectric loss angle 'δ' of the capacitor, which is the angle whose tangent is the ratio of the losses to the reactive power reduced (Collombet et al., 1999).
- Machines and transformer heating: for the rotating machines, losses in the stators (copper and iron) and mainly in the rotors (damping windings, magnetic circuits) of machines caused by the high differences in speed between the harmonic inducing rotating fields and the rotor main field. In the transformers there will be additional losses result from the skin effect (increase in the copper resistance with frequency), eddy and hysteresis currents in the magnetic circuits (Collombet et al., 1999).
- Cable heating: there will be temperature rise in the cables that are polluted with harmonics, this is because there will be additional losses in cables. The factors that cause heating are increasing in the current effective due to harmonics, increasing in the core resistance with harmonics frequency due to the skin effect, and increasing in the cable dielectric losses with the frequency due to harmonics distortion in the voltage (Collombet et al., 1999).
- Electrical switchboard heating: if the electrical switchboards are subjected to voltage harmonics due to harmonic currents flow, there will be additional energy losses and in this case the switchboard should be thermally derated. For example, a capacitor feeder switchboard should be designed for a current which is greater than the reactive compensation

rated current. Mainly, this safety factor should be taken to consider with the increased heating due to harmonic thermal stresses (Collombet et al., 1999).

1. Harmonic Filters and Power Qality

According to IEC standards, in the LV distribution networks, before implementing capacitor banks there should be preliminary study for the main low voltage switchboard (MLVSB),this study is mainly concerned with the weight of the nonlinear loads (G_h in MWatt) to the rated apparent power of the MV/LV transformer that feeds the MLVSB (S_{rated} in MVA), for [G_h / S_{rated}] is less than 50% the filter solution is not applicable, in case of [G_h / S_{rated}] is greater than 50% the filtration action should be taken to suppress the harmonic distortion in the network (IEC 61642, 2010). There are two types of harmonic filters (Harmonics, 2011),

- Shunt Active Filter: this type of filters has become a mature technology in recent years. The function principle of active filter is based on a pulse width modulation three-phase inverter to generate non-sinusoidal currents to meet harmonic current requirement of the nonlinear load, it generates a wave anti of phase with the existed harmonics, and then it injects this anti phase wave to network again to suppress the network harmonics (Bettega and Fiorina, 1999; Tain-Syh Luor, 2000). Fig. 1 shows a schematic diagram to clarify the active filter operation in the LV distribution network; also, it shows current waveforms in different location of the distribution networks during the active filter operation (Johnson, 2008). Many literatures have carried out the configurations, control strategies, and applications of active filters (Singh et al., 1999).

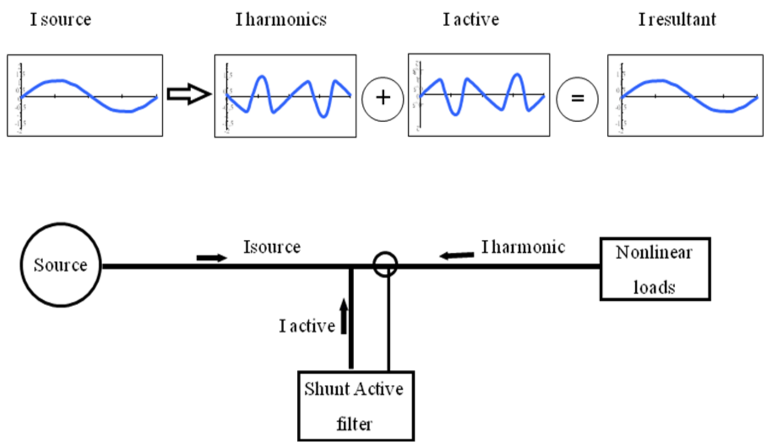

Fig 1: Active filter operation in the LV distribution network

One of the active filter advantages that it can eliminate the harmonics up to 40th order and the main disadvantage is the high cost of the active filter device (Bettega and Fiorina, 1999).

Passive harmonic filters are identified as trap filters and broadband filters employ inductors (L) and capacitors (C) in arrangements to cancel a specific harmonic frequency (trap filters) or a wider spectrum that may include harmonics up to the 17th order (broadband). While these devices do perform the harmonic reductions, they inject leading reactive current that may cause the electrical system to have a leading power factor. This type of filters injects leading reactive current and boosts the voltage and increases the possibility of system resonance (Johnson, 2008). If there is dominant order of harmonics a passive filter is designed to act as a sink of this dominant harmonics; so, it eliminates a certain order of harmonics (3rd order, 5th order, 7th order, or 9th order). This is considered one of the major disadvantages of the passive filter with the possibility of system resonance (Bettega and Fiorina, 1999).

2. Proposed Algorithm and Modeling

Consider a MLVSB with a group of linear and nonlinear loads, the loads of this switchboard are highly inductive, and there is mandatory to have power factor correction by adding capacitor banks. The capacitor bank units are switched ON/OFF automatically by a certain reactive power controller to have a targeted power factor with load variation. The capacitor bank type may be standard, overrated, or overrated plus detuned reactor (IEC 61642, 2010), in this research the standard capacitor bank is used to highlight the harmonic phenomena with high level of nonlinear loads penetration [G_h / S_{rated} ≥ 50%], the standard capacitor bank causes amplification of the harmonics to a certain level where the filtration is mandatory. This research presents a comparison between passive and active filtering when both are implemented to mitigate the harmonic distortion in the level of MLVSB and suggest a suitable size of active filter that suppress the harmonics to satisfactory level without additional cost of oversized active filter.

Figure 2 shows the MLVSB under study, the switchboard includes both types of loads (linear and nonlinear) and fed from MV/LV transformer with 'S_{rated}' kVA. The MLVSB is extended by capacitor bank cubicle to compensate the low power factor and it has a possibility to be equipped with both types of harmonic filters. HARENA software is used to simulate the MLVSB and make comparison between both techniques of filters. While implementing the active filter all obtained data are sent to MATLAB m-file to choose the size of the active filter based on the achieving the targeted THD in voltage that match with environment standard value.

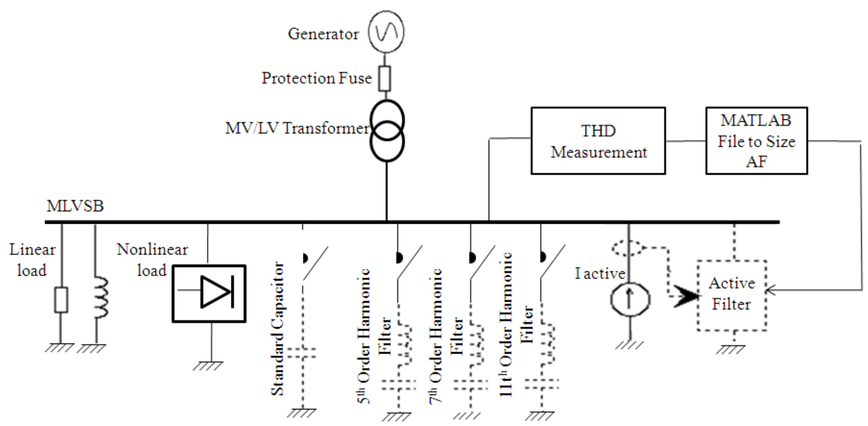

Fig.2: MLVSB with different harmonic filters techniques.

2.1 MLVSB Electrical Data:

- Generator: Deliver power to the MV/LV transformer with frequency 'f = 50 Hz' and short

circuit power of the utility 'MVA_{sc} = 150 MVA'
- MV/LV Transformer: 6.6kV/400V and rated power of 630kVA and short circuit voltage of 6%

- Loads: linear heavily inductive loads with total active power of 120kW at 0.82 PF lagging. Nonlinear loads that generate harmonics in the distribution network based loads and it is taken as 'Gh' of 380kW at 0.86 PF lagging.

- Target Power factor of this switchboard is 0.92, and allowable THD in voltage is 5.2% ($THDv_{ref}$).

- Standard capacitor bank is implemented to correct the power factor to the targeted value.

- Passive filters with orders 5, 7, and 11 respectively to suppress the harmonics, table I present the ratings of the available filters, that are suitable with the case study,

- Active filter (AF) with adaptive rated current to mitigate the harmonics to be within the allowable standard range ($THDv_{ref}$).

2.2 Standard Capacitor Bank Sizing:

Referring to the electrical data of the MLVSB there is a need to improve the power factor with banks of capacitors, the size of those banks is automatically calculated by (Saadat, 1999),

$$Q_c = \sum P_{load} (\tan\varphi_1 - \tan\varphi_2) \qquad (2)$$

where,

Q_c: kVAR of the implemented capacitors, $\sum P_{load}$: the sum of total active power connected to panel, φ_1: the power angle without correction, and φ_2: the targeted power angle.

Accordingly, the reactive power controller begins to engage the capacitor units into service till achieving the targeted power factor.

HARENA software is concerned with THD measurements with and without capacitor bank to correct the power factor, also, the THD is measured after applying filtering solution by either passive or active filters. If the AF is recommended, MATLAB file is programmed to get step increasing in the AF current, this increasing is continuous till obtaining the targeted standard THDv that keeps the network operation with high level in power quality. The proposed algorithm is illustrated in Fig. 3 where the filtering action is taken when there is high penetration of the nonlinear loads ($[G_h / S_{rated}] \geq 50\%$).

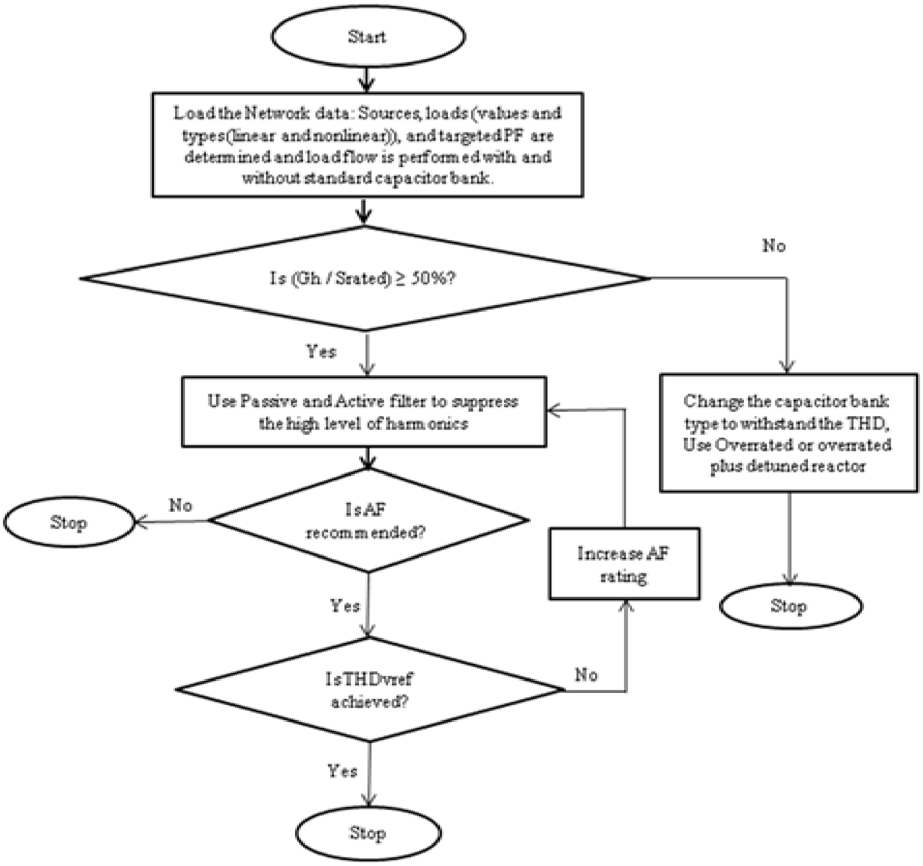

Fig. 3. Flow Chart of Filter Actions in the LV Distribution Networks

The proposed algorithm shows that if [G_h / S_{rated}] < 50% the solution in changing the capacitor bank type without filter implementation (IEC 61642, 2010) and this is out of research scope where the research is concerned with only high penetration of nonlinear loads.

3. Simulation Results

3.1 Results without Capacitor and With Passive Filters

In this part, the customer has no capacitor bank to correct the power factor, the high penetration of the nonlinear loads causes the THDv and THDi increases above the allowable standard levels. The filter action should be taken to suppress this high level of harmonics. Figure 4 presents the harmonic spectrum in case of [G_h / S_{rated}] ≥ 50%, without capacitor bank installation and without harmonic filter implementation. The major harmonic orders are the 5^{th}, 7^{th}, and 11^{th}. So, Fig. 5 shows the effect of 5^{th} order passive filter. Both 5^{th} and 7^{th} order filters are used in Fig. 6 and the three filters are used in Fig. 7 where the harmonic suppression is clear. Table II shows the obtained measurements related to the previous results, single and double passive filters could not attain the targeted THDv which is achieved with the three filters implementation. Thus, there is need to use three passive filters to get the THDv back into the allowable range (%THDv = 3.22).

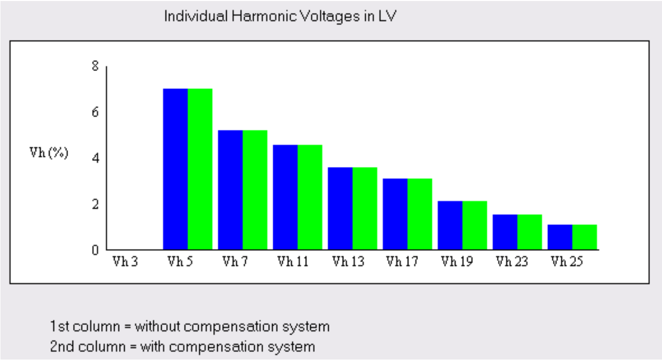

Fig. 4. Voltage Harmonic Spectrum without Capacitor and without Filters

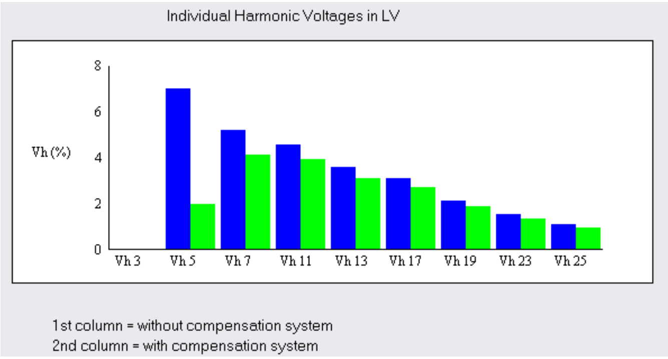

Fig. 5. Voltage Harmonic Spectrum without Capacitor and with 5th order Passive Filter

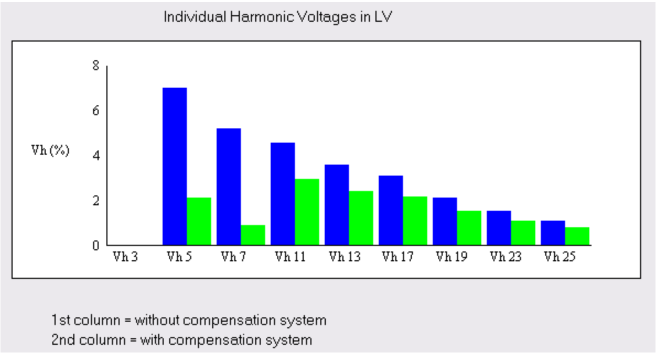

Fig. 6. Voltage Harmonic Spectrum without Capacitor and with both 5th and 7th order Passive Filters

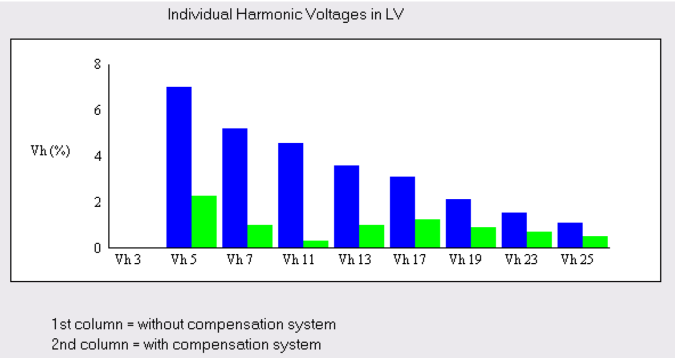

Fig 7: Voltage Harmonic Spectrum without Capacitor and with 5th, 7th, and 11th order Passive Filters

3.2 Results with Capacitor and With Passive Filters:

Standard capacitor bank is suggested to correct the power factor to the target value, this aggravates the harmonic distortion as Fig. 8 illustrates. Fig. 9 shows the effect of 5th order passive filter. Both 5th and 7th order filters are used in Fig. 10 and the three filters are used in Fig. 11 where the harmonic suppression is clear.

Table III shows that although the three passive filters are used, the harmonic will be suppressed but to value which is greater than the targeted value. Thus, the passive filters are not the proper filtration method to mitigate the harmful effects of the harmonics.

Now, the implementation of the active filter is mandatory and recommended to restore the harmonics into the targeted level to enhance the power quality.

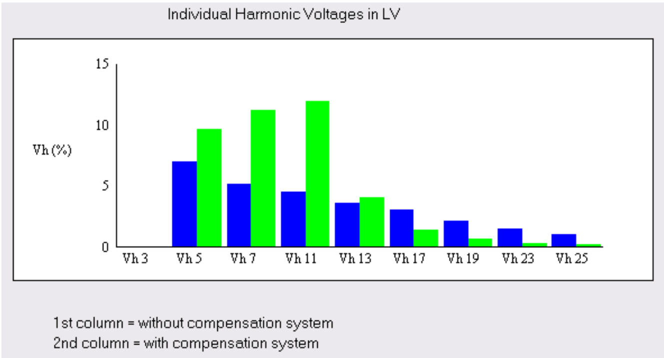

Fig. 8. Voltage Harmonic Spectrum with Capacitor and without Filters

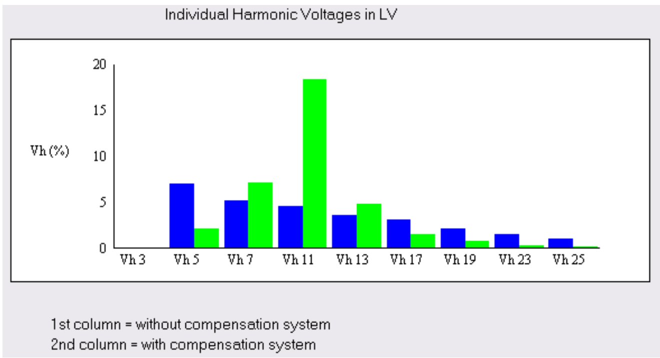

Fig. 9. Voltage Harmonic Spectrum with Capacitor and with 5th order Passive Filters

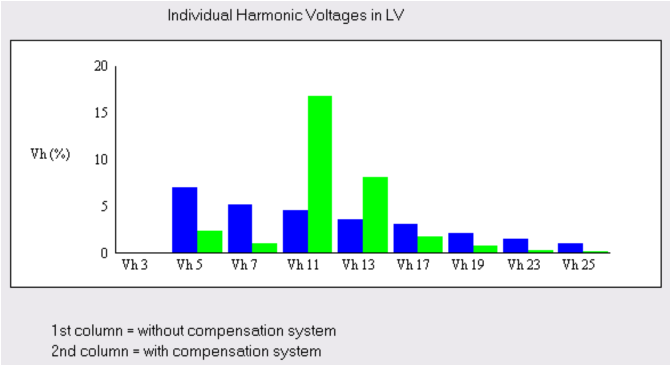

Fig. 10. Voltage Harmonic Spectrum with Capacitor and with both 5^{th} and 7^{th} order Passive Filters

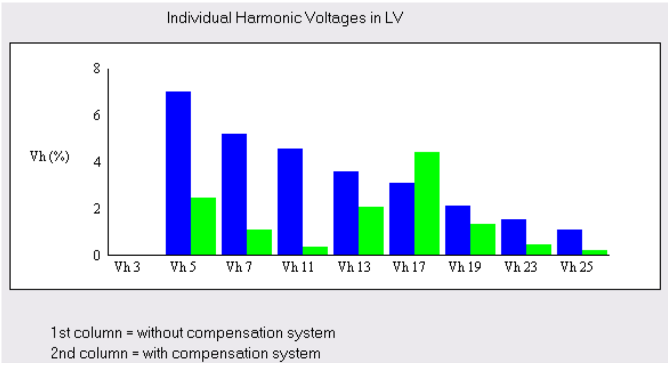

Fig. 11. Voltage Harmonic Spectrum with Capacitor and with 5^{th}, 7^{th}, and 11^{th} order Passive Filters

3.3 Results with Active Filters:

HARENA software is used to simulate the active filter to be connected to the MLVSB to suppress the harmonics by anti-harmonic current injection. To get the suitable size of that filter the quantity of the injected current is given in steps by M-file under MATLAB software that takes the corresponding THDv from HARENA to compare with the targeted value. The desired value of the AF current is that corresponding to the targeted %THDv. Figure 12 presents the relation between the anti-harmonic current generated from the AF and the corresponding THDv, by intersection of that relation with the targeted THDv, the adequate ratings of the AF that retain the %THDv into the allowable range is accurately determined, this is in both cases of with and without capacitor bank implementation. Also, the filter current is determined to have zero THDv which is optimum case.

Figure 13 shows the effect of active filter on the harmonic spectrum, the AF is prospered to retain the targeted value of %THDv to 5.2 with 130A – rating (see Fig. 12), this is without standard capacitor to correct the power factor. Similarly, with capacitor bank implementation, Fig. 14 illustrates the AF effect with rating current greater of 177A (see Fig. 12), the targeted level harmonic distortion has been successfully achieved, this is on contrary with the passive filters that have been failed to achieve.

The results show that, there should be increasing in the AF anti-harmonic current (from 130A to 177A) to encounter the harmonics aggravation caused by capacitor bank.

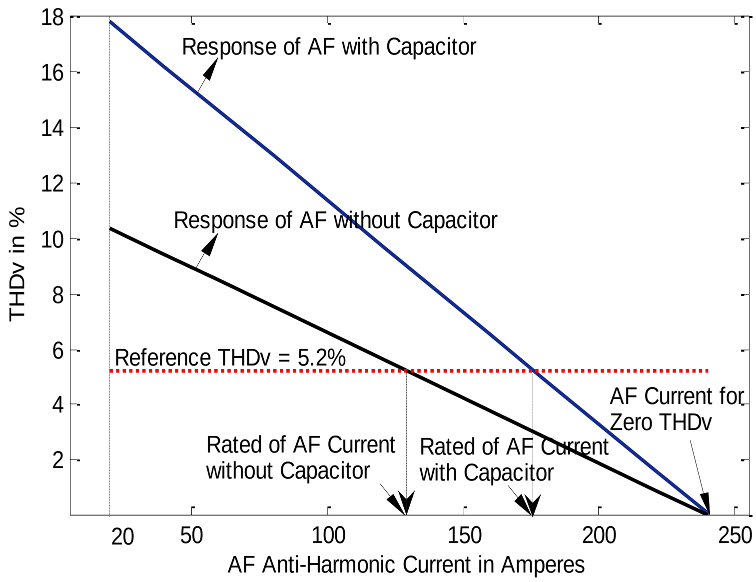

Fig. 12. Active Filter Sizing to Retain the Targeted THDv.

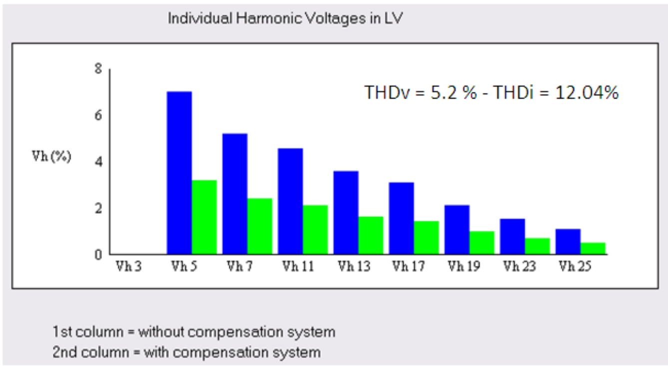

Fig. 13. Voltage Harmonic Spectrum **without** Capacitor and with **133A** Active Filter

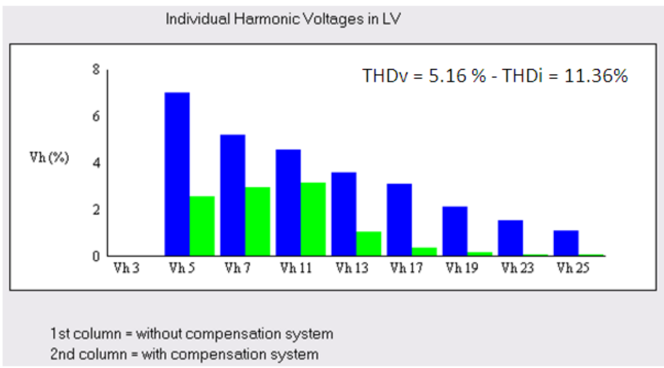

Fig. 14. Voltage Harmonic Spectrum **with** Capacitor and with **177A** Active Filter

4. Conclusion

This paper addressed the power quality problem associated with the high penetration of the nonlinear loads in the low voltage distribution network, this leads to increase the harmful effects of the harmonics that may cause damage or destroy some sensitive loads. Standard capacitor bank units aggravates the harmonic problems and leads to more power quality deterioration. This research proposes the harmonics filters as to mitigate the previous bad effects.

In case of high penetration level of nonlinear loads, one passive filter may be not enough to suppress the harmonics to be within the allowable limit, so, many orders of passive filters have been used to give cumulative and corrective response. This response is capable to retain the targeted level of the THDv. In case of high level of penetration level with standard capacitor banks, the multiple orders of passive filters have been failed to retain the harmonics to the allowable limit, thus, the AF is suggested to mitigate the harmonics instead of the passive units. The results show that the AF is proficient to manage any level of harmonics to be under the targeted level. The superiority of AF on the passive type is proved for the network with standard capacitor banks. Also, for the recommended AF solution, The AF-ratings for targeted THDv and zero THDv have been precisely identified. This appropriate sizing of AF reduces its module cost which is one of the major disadvantages of the AF intervention.

References

Bettega E. and Fiorina J. N., (1999), Cahier Technique no. 183: Active harmonic conditioners and unity power factor rectifiers, Schneider Electric, 1st edition,

Calvas R., 2012, Electrical Disturbances in Low Voltage, Cahier Technique no.141, Schneider Electric,.

Collombet, C., Lupin, J. M., & Schonek, J. (1999). Harmonic disturbances in networks, and their treatment. *Cahier Technique Merlin Gerin*, (152), 28.

Dugan, R. C., McGranaghan, M. F., & Beaty, H. W. (1996). Electrical power systems quality. New York, NY: McGraw-Hill,| c1996, 1.

Harmonics, (2011), Characteristic Parameters, Methods of Study, Estimates of Existing Values in the Network, (ELECTRA) CIGRE 07/81.

IEC 146-2: Semiconductor Converters, 2010

IEC 61642, (2010) Industrial AC Networks Affected by Harmonics – Application of Filters and Shunt Capacitors,.

Johnson, J. R. (2008, September). Managing harmonics and resonance with active harmonic filters in an offshore ring main oil field. In *Harmonics and Quality of Power, 2008. ICHQP 2008. 13th International Conference on* (pp. 1-8). IEEE.

Singh B., AI-Haddad K., and Chandra A., (October 1999), A review of active filters for power quality improvements, IEEE Trans. on Industrial Electronics, vol. 46, no. 5, , pp. 960-971.

Tain-Syh Luor, (2000), Influence of Load Characteristics on the Applications of Passive and Active Filters, Ninth ICHQP, vol.1, pp. 128-133.