Journal of Advanced Science and Engineering Research Vol 4, No 3 September (2014) 157-167

Investigation of Capacitor-Bank Type Controller to Enhance the Power Quality in the Low Voltage Distribution Networks

Walid Helmy

Electrical Power and Machines Department
Ain Shams University, Cairo, Egypt

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

Article Info

Received: 18/ 8/2014
Accepted: 29/8/2014

ISSN 2231-8844

ABSTRACT

This paper studies the effect of implementing different technologies of capacitor bank manufacturing on the power quality of the low voltage distribution networks. With the widespread of power factor correction in the industrial sites, the customers have to choose between different types of capacitor banks in the market. These types are classified according to the existing harmonic levels existed in the low voltage switchboard. The ratio between the non-linear loads and the rating of medium voltage to Low voltage (MV/LV) transformer determines put forward the suitable type of the capacitor bank. The implementation of the capacitor banks in the distribution network has a direct impact on the harmonic levels; this may lead to destroy the capacitor itself due to thermal effect of that harmonics. In the research, by realizing HARENA software, the impact of different types of the capacitor bank on a main low voltage distribution board (MLVDB) is illustrated, also, the MATLAB software is applied to investigate a controller that automatically switches the suitable capacitor bank type according to online measurements of the total harmonic distortion in voltage (THD¬) existed in the level of the MLVDB, accordingly, the capacitor-bank type is recommended to withstand or attenuate the harmonics and the power quality is enhanced

Keywords: Power Factor Correction, Capacitor Banks, Low voltage Switchboard, Harmonic Analysis, Power Quality.

1. INTRODUCTION

With the widespread of large industrial loads on the level of distribution networks, the electricity bill is very expensive due to high consumption and due to penalty of low power factor, there is need to improve the power factor to avoid the previous dramatic scenarios. Also, with the application of modern technologies in the industry (electronics and micro-processor based), the nonlinear loads are continuously increased, these nonlinear loads generate harmonics and cause sharp increasing in the total harmonic distortions in both current and voltage (Dugan et al., 1996). The capacitor banks that are used to improve the power factor amplify the harmonics generated from the nonlinear loads that are considered harmonic generators, this harmonic amplification may destroy the some capacitor units in the bank (Dugan et al., 1996). According to IEC standards, in the LV distribution networks, there are three types of capacitor banks in the industry, this is according to the weight of the nonlinear loads (G_h in MWatt) to the rated apparent power (S_{rated} in MVA) of the MV/LV transformer that feeds the MLVDB,

- *Standard (classic) capacitor:* this is traditional type of capacitor with dielectric material that can withstand the rated voltage of the LV networks. This type of capacitor banks amplify the harmonics, so, this type is implemented in case of the following condition (IEC 61642, 1997),

$$(0 < G_h / S_{rated} < 15\%).$$

- *Overrated (Comfort) capacitor:* this type of capacitor is manufactured with dielectric material that can withstand overvoltage up to 40% above the rated voltage of the LV networks. This type also amplify the harmonics but it can withstand the thermal stresses of harmonics than the standard type, so, this type is implemented in case of the following condition (IEC 61642, 1997),

$$(15\% < G_h / S_{rated} < 25\%).$$

- *Overrated plus detuned reactor (Harmony) capacitor:* this is the same overrated capacitor but with series detuned to coil to reject the higher level of harmonic distortion. This type is implemented in case of the following condition (IEC 61642, 1997),

$$(25\% < G_h / S_{rated} < 40\%)$$

The detuned reactor is a coil in series with the capacitors to make a barrier to prevent the harmonic penetration through the capacitor banks, so, there will be reduction in the level of harmonic amplification due to power factor correction capacitors. The detuned reactor must have no resonance with the capacitor at either fundamental or harmonic frequencies, so, there are three types 'orders' of the detuned reactor:

- **Order '2.7':** where this reactor will make resonance with capacitor at 165Hz,
- **Order '3.8':** where the resonance will occur at 230Hz, and
- **Order '4.3':** where the resonance will occur at 280Hz.

It is obvious that for any operating frequency (fundamental or harmonics), it is impossible to have tuning or resonance between the detuned reactor and capacitor banks (IEC 61642, 1997). For [G_h / S_{rated}] is greater than 40% the filtration action should be taken to decrease the harmonic distortion in the network. There are two types of harmonic filters (CIGRE, 1981),

- Active Filter: this type of filter generates a wave anti of phase with the existed harmonics, and then it injects this anti phase wave to network again to vanish the network harmonics. Figure 1 shows a schematic diagram to clarify the active filter operation in the LV distribution network (Bettega & Fiorina, 1999). .

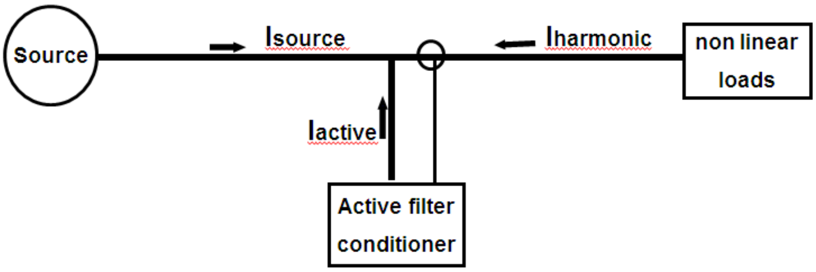

Figure 1: Active filter operation in the LV distribution network.

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.

- Passive Filter: 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 (Bettega & Fiorina, 1999).

2. POWER FACTOR CORRECTION AND POWER QALITY

Operation of the low voltage distribution network under low power factor has a multiple disadvantages like,

- Increasing in the electrical energy bill,
- Power losses increasing,
- Deterioration of voltage regulation due to voltage drop, and
- Over-sizing of the cables and transformers that fed this distribution networks (Barsoum, 2007).

Implementing of the capacitor bank switchboards is very important to improve the power factor and avoid distribution network deterioration. Power factor capacitor has a certain incompatibility where,

- Although capacitors do not cause harmonics they can aggravate existing conditions,
- Capacitors naturally have low impedance to high frequencies in other words the capacitors absorb harmonics

$$X_c = 1 / (2\pi f_c) \qquad (1)$$

- As capacitor absorbs harmonics, the capacitor heats up, so, reduced life expectancy (IEEE 519 Working Group, 1992).

This research is concerned with the power quality of the LV distribution network, from the previous power factor incompatibility the power quality of the LV distribution networks is subjected to optimization between improving the power factor and minimize the harmonic bad effects in that networks.

3. PROPOSED ALGORITHM AND MODELING

Consider a MLVDB 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, in this research there is investigation of novel controller to have automatic engagement of the suitable type of capacitors, this controller will be added to the reactive power controller to have a proper power factor correction with power quality consideration. The proposed controller action depends on online measurements of the total harmonic distortion (THD) with detection of the ratio (G_h / S_{rated}).

Figure 2 shows the MLVDB under study, the switchboard includes both types of loads (linear and nonlinear) and fed from MV/LV transformer with 'S_{rated}' kVA. The MLVDB has a possibility to be extended by capacitor banks with different types, the value of capacitors is controlled by reactive power controller and the type is controlled by the proposed controller, this controller is programmed by MATLAB software to switch ON the suitable type of the capacitor based on the online measurement of the total harmonic distortion.

3.1 MLVDB 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 'PL' in kW at 0.82 PF lagging. Nonlinear loads that generate harmonics in the distribution network based loads and it is taken as 'G_h' in kW at 0.86 PF lagging.

N. B.: To study the impact of the nonlinear loads, 'G_h' is variable but the sum of all loads equals 500kW.

- Target Power factor of this switchboard is 0.92, and allowable THD in voltage is 5.2%.

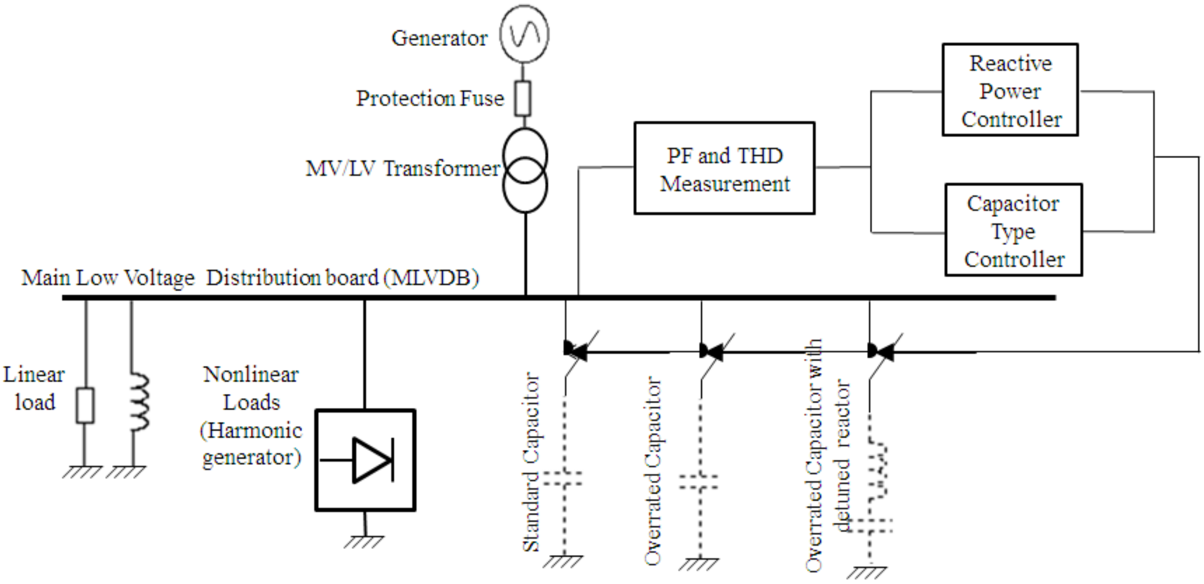

Figure 2: MLVDB with Different Types of Capacitor banks.

3.2 Capacitor Bank Size and Type:

Referring to the electrical data of the MLVDB 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, also, the capacitor type controller choose the suitable type of the capacitor banks according to the THD in the level of the MLVDB taking into account that the capacitor has an amplification impact to the harmonic existence.

HARENA software is concerned with THD measurements and according to those measurements MATLAB software is used with if conditions to select the suitable type of the capacitor to achieve the targeted power factor with avoidance of capacitor damage under harmonic circumstances. Figure 3 presents the flow chart that illustrates the steps that should be followed to achieve proper power factor correction.

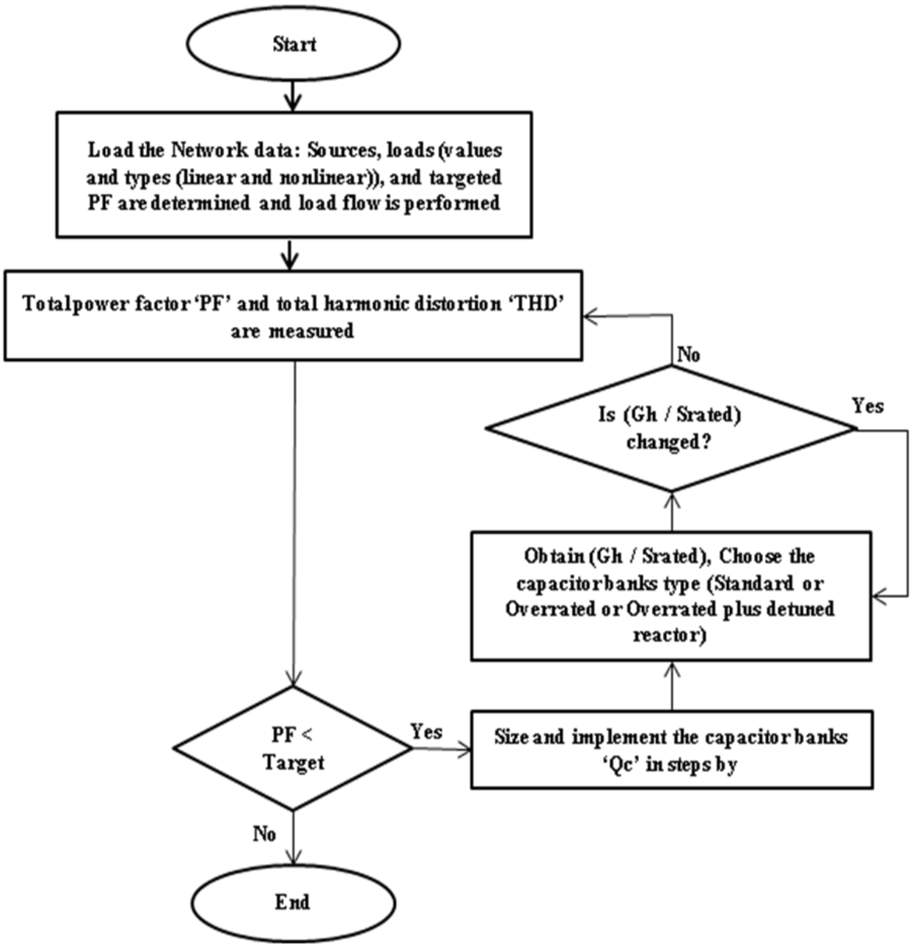

Figure 3: Flow Chart of Proper Steps for PF Correction.

4. SIMULATION RESULTS

4.1 Results Without Capacitor Type Controller:

In this part, the customer install one type of capacitor bank, this type is subjected to different operating modes where the ratio (G_h/S_{rated}) is varying for the same capacitor type, the capacitor bank life cycle will be reduced due to thermal stresses of the harmonics that are generated by the nonlinear loads.

- ***Results with (G_h/S_{rated}) = 11.1%***

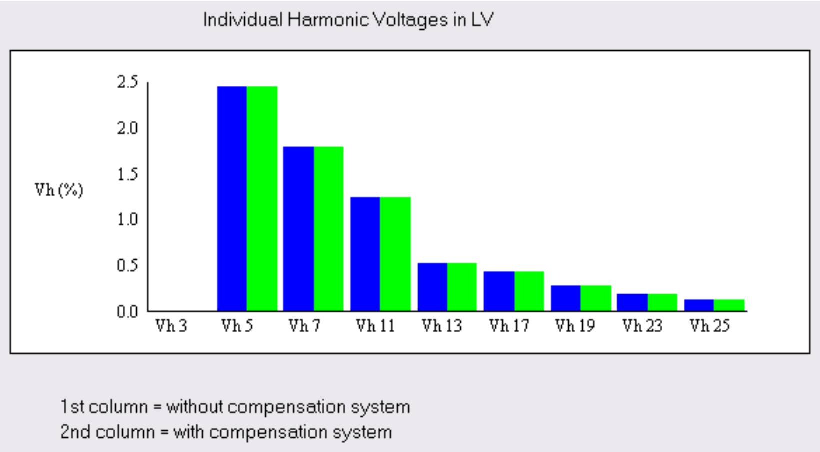

Figure 4: Voltage Harmonic Spectrum without Capacitor

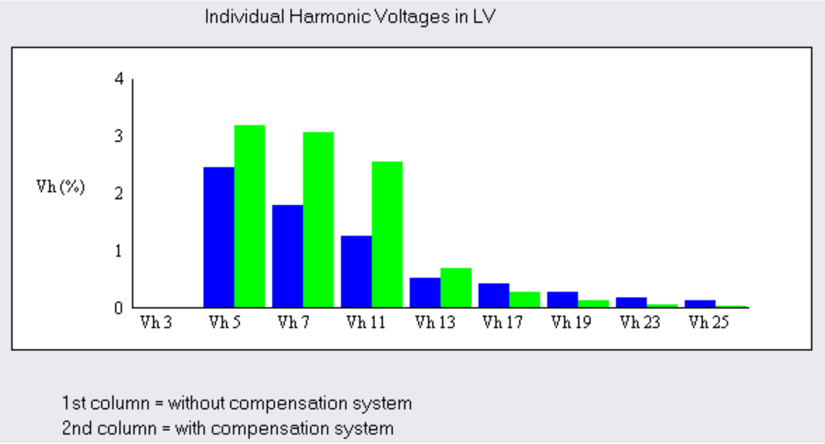

Figure 5: Voltage Harmonic Spectrum with standard capacitor

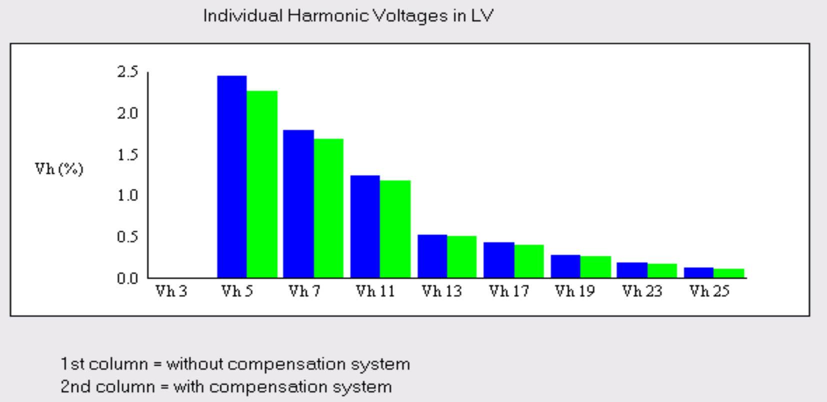

Figure 6-a: Voltage Harmonic Spectrum with overrated plus Detuned Reactor capacitor 'order 2.7'

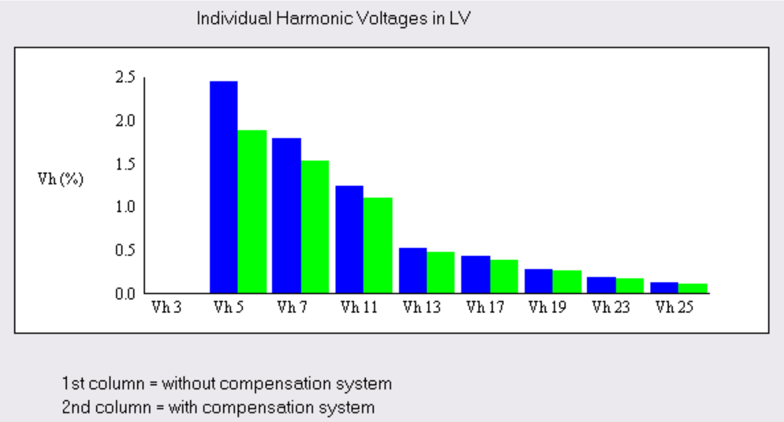

Figure 6-b: Voltage Harmonic Spectrum with overrated plus Detuned Reactor capacitor 'order 3.8'

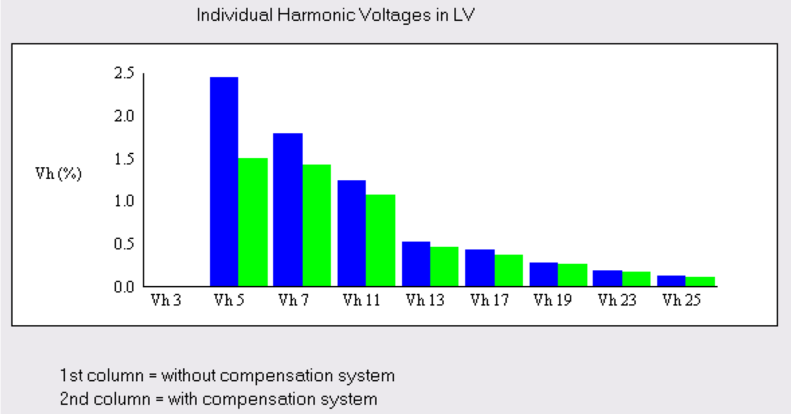

Figure 6-c: Voltage Harmonic Spectrum with overrated plus Detuned Reactor capacitor 'order 4.3'

Figure 4 shows the voltage harmonic spectrum due to the nonlinear load without power factor improvement. Figure 5 show the harmonic amplification due to implementing of standard capacitor. Figures 6-a, 6-b, and 6-c show the attenuation done for the harmonics due to implementing overrated capacitor bank plus detuned reactor with order 2.7, 3.8, and 4.3 respectively. In case of overrated capacitor only, the results of the standard capacitor are obtained, so, it amplifies the harmonics but it can withstand more stresses than the standard type.

Table 1: Summary of Measurements for (G_h/S_{rated}) = 11.1%

Modes	THD% in 'V'		THD% in 'I'
	MV	LV	LV
No Qc	2.68	3.38	4.99
Standard	2.72	**5.17**	8.77
detuned 2.7	2.67	3.15	4.73
detuned 3.8	2.65	2.77	4.54
detuned 4.3	2.63	2.43	4.65

From table 1, although there is amplification of the harmonics due to using of standard capacitor, the limit of THD in voltage still within acceptable limit and no need for detuned reactor where both standard and overrated types are sufficient to withstand the consequential stresses.

- ***Results with (Gh/Srated) = 31.0%***

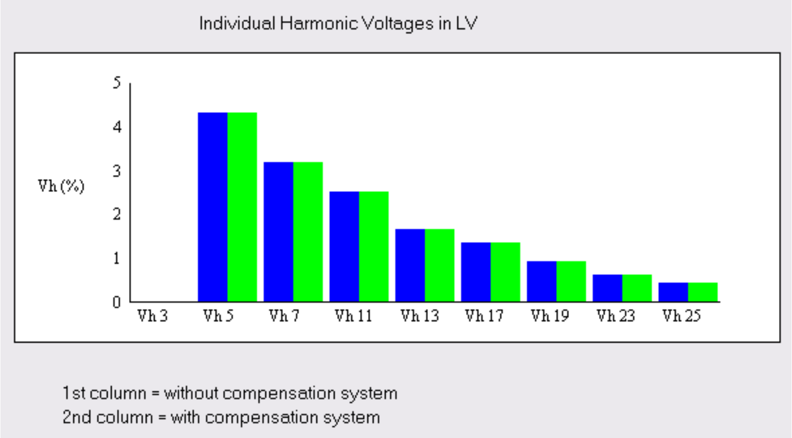

Figure 7: Voltage Harmonic Spectrum without Capacitor.

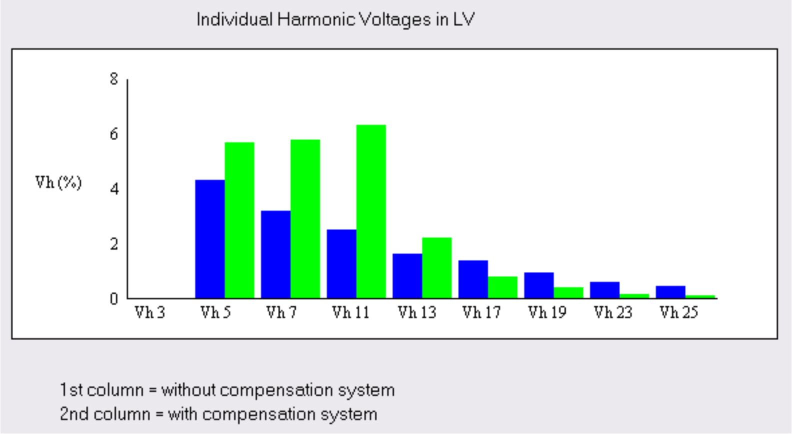

Figure 8: Voltage Harmonic Spectrum with standard capacitor

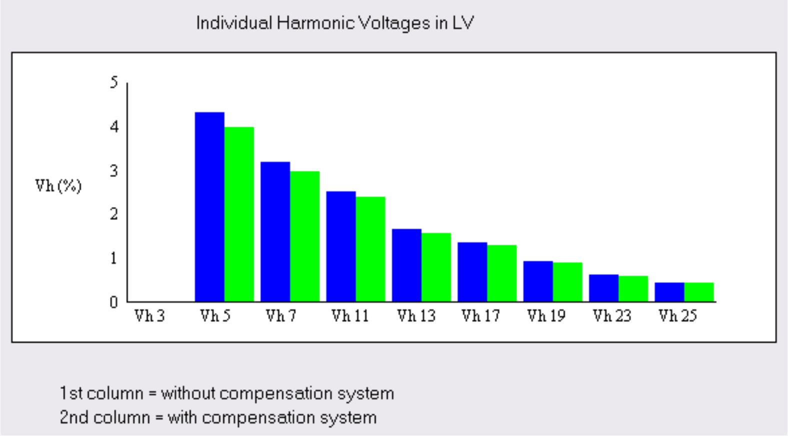

Figure 9-a: Voltage Harmonic Spectrum with overrated plus Detuned Reactor capacitor 'order 2.7'

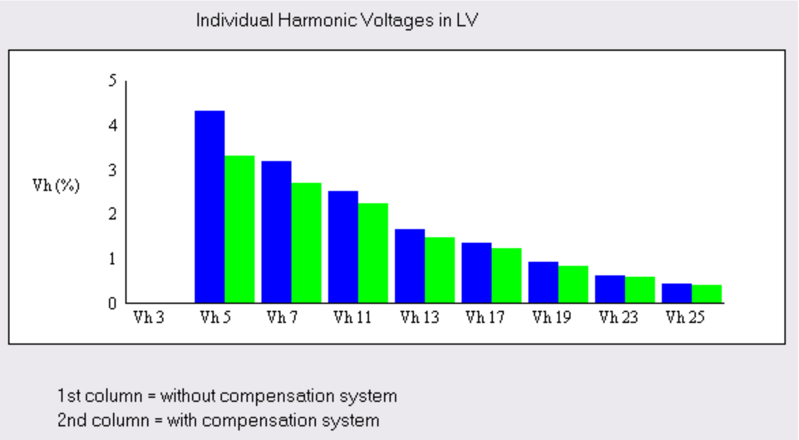

Figure 9-b: Voltage Harmonic Spectrum with overrated plus Detuned Reactor capacitor 'order 3.8'

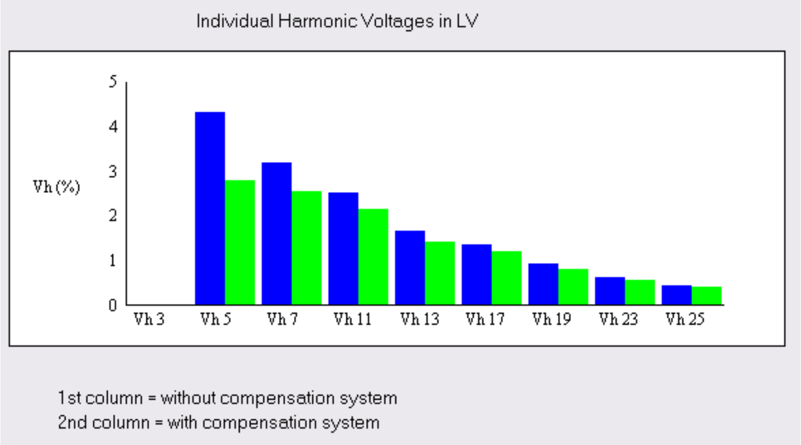

Figure 9-c: Voltage Harmonic Spectrum with overrated plus Detuned Reactor capacitor 'order 4.3'

Figure 7 shows the voltage harmonic spectrum due to the nonlinear load without power factor improvement. Figure 8 show the harmonic amplification due to implementing of standard capacitor. Figures 9-a, 9-b, and 9-c show the attenuation done for the harmonics due to implementing overrated capacitor bank plus detuned reactor with order 2.7, 3.8, and 4.3 respectively. In case of overrated capacitor only, the results of the standard capacitor are obtained, so, it amplifies the harmonics but it can withstand more stresses than the standard type.

Table 2: Summary of Measurements for (G_h/S_{rated}) = 31.0%

Modes	THD% in 'V'		THD% in 'I'
	MV	LV	LV
No Qc	2.75	6.64	12.93
Standard	2.86	**10.57**	20.90
detuned 2.7	2.73	6.00	12.03
detuned 3.8	2.70	5.30	10.63
detuned 4.3	2.68	**4.87**	9.79

From table 2, when the nonlinear loads are increased and reached 31% of the transformer rating, the implementing of standard capacitor banks amplify the THD% in the low voltage side to be more than the allowable limit (5.2%), thus, this type of capacitor is not suitable to correct the power factor, and it will be damaged if it is continuously used in service to improve the power factor, also, the same results will be obtained if the overrated capacitors are implemented. There is mandatory to use overrated capacitor plus detuned reactor with order '4.3' where both orders of '2.7' and '3.8' are failed to reduce the THD% again into the desired allowable range.

4.2 Results With Capacitor Type Controller:

From the results that have been obtained from part 'A', the proposed automatic controller is taking online measurements and monitoring from the MLVDB and accordingly it contacts the suitable type of the capacitor bank that situates the recent loading conditions of the distribution panel.

For loading condition with **$(G_h/S_{rated}) = 11.1\%$,** it gives an order to close the contactors of standard type capacitors to be in service, this guarantees that the allowable limit of THD in voltage is not violated where it is less than **5.3%.**

When the condition is changed to **$(G_h/S_{rated}) = 31.0\%$,** the controller delivers an order to close the contactors of the overrated capacitors plus detuned reactor with '4.3' order to be in service. Thus, the THD in voltage will be less than the allowable limit. Thus, with different loading conditions, the proposed automatic controller that choose the capacitor type is succeeded to improve the power factor taking into account the harmonic distortion issue. The harmonic distortion issue has a great impact on the power quality in the level of low voltage distribution networks.

5. CONCLUSION

This paper addressed the power quality problem associated with the implementation of capacitor bank units in service to make power factor compensation. In most industries with heavily inductive loads the customer must choose a suitable type of capacitor banks to improve the power factor, this action must be taken to avoid technical and economical disadvantages that are existed due to operation under low power factor condition, also, the penetration of nonlinear loads in the LV distribution network is continuously increasing. There should be optimization between PF correction and harmonic amplification that is caused by this correction. This research illustrates online monitoring controller to choose the suitable type of capacitor banks that matching with the existed harmonics to guarantee operation under allowable limit of the THD in the voltage.

Without the proposed controller it is preferable to choose the overrated capacitor banks with detuned reactor to withstand any level of harmonic stresses and attenuate the THD in the voltage to be within the acceptable limit. This case may lead to thermal aging of this type of capacitor bank.

If there is cost availability to have the three types of capacitor banks in the panel, the proposed controller chooses the suitable type that situate with the existed harmonic levels, so, for any certain harmonic level or nonlinear load penetration level, the controller selects the suitable type of capacitor banks. This leads to increase the power quality level with increasing the life time of the capacitor bank units in the panel. Thus, in case of power factor correction, the research recommends to implement capacitor type controller in addition to reactive power controller to coordinate between power factor correction and harmonic existence the LV distribution networks to enhance the power quality.

6.REFERENCES

Abdel Aziz M. M., Abou El-Zahab E. E., Ibrahim A. M., and Zobaa A. F., (2004), LC compensators for power factor correction of nonlinear loads," *IEEE Trans. Power Delivery*, vol. 19, no. 1, pp. 331–336, Feb. 2004.

Barsoum, N. (2007, March). Programming of PIC micro-controller for power factor correction. In *Modelling & Simulation, 2007. AMS'07. First Asia International Conference on* (pp. 19-25). IEEE.

Bettega, E., & Fiorina, J. N. (1999). Active harmonic conditioners and unity power factor rectifiers. Cahiers Techniques..

Cavallini, A. Ghinello, I. Mazzanti, G. and Montanari G. C., (1999), Consideration on the life performance and installation of shunt capacitors in the process of harmonics generated by AC/DC converters," IEEE Trans. Power Delivery, vol. 14, pp. 227–234, Jan. 1999.

CIGRE, W. (1981). 36-05:" Harmonics, characteristic parameters, methods of study, estimates of existing values in the network. *Electra*, *77*, 35-54.

Detjen D., Jacobs J.,. De Doncker R. W, and Mall H. G., (2001), A new hybrid filter to dampen resonances and compensate harmonic currents in industrial power systems with power factor correction equipment," *IEEE Trans. Power Electron.*, vol. 16, no. 6, pp. 821–827, Nov. 2001.

Dionise T. J. and Lorch V.,(2006), Harmonic filter analysis and redesign for a modern steel facility with two melt furnaces using dedicated capacitor banks," in *Proc. IEEE-IAS Annu. Meeting*, 2006, pp. 137–143.

Dugan, McGranagan, and Beaty, (1996),"Electrical Power Systems Quality,", McGraw Hill, US,.

Girgis, A. A. Fallon C. M., Rubino C. P., and Catoe R. C., (1993), Harmonics and transients overvoltages due to capacitor switching," *IEEE Trans. Ind. Appl.*, vol. 29, no. 6, pp. 1184–1188, Nov./Dec. 1993.

Grebe T. E., (1996), Application of distribution system capacitor banks and their impact on power quality," *IEEE Trans. Ind. Appl.*, vol. 32, no. 3, pp. 714–719, May/Jun. 1996.

IEC 61642, (1997), Industrial ac Networks Affected by Harmonics – Application of Filters and Shunt Capacitors, -09-01

IEEE 519 Working Group. (1992). IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. *IEEE STD*, 519-1992.

Saadat, H. (1999). *Power system analysis*. WCB/McGraw-Hill.