

Design of Harmonic Filter for AL-Tahady Electro Static Precipitator System

¹Taha N. DeKheel, ²Mohammed O. Mustafa, ³Mehdi J. Marie

^{1,2}Electrical Engineering Department, University of Mosul, Mosul, Iraq

³Al-Zawraa State Company, Ministry of Industry and Minerals, Baghdad, Iraq

Abstract - The use of non-linear loads, such as electro static precipitator (ESP) and variable speed drive (VSD), draws much distorted currents and voltages. They lead to generation of voltage/current harmonics and consume reactive power. Al-Tahady ESP had been designed and manufactured at Al-Zawraa state company as an air pollution control system. This paper presents the solution for this problem, firstly a separation of power supplies led to proper operation of the system, this secondly encourages to think of harmonics generated by variable speed drive. The three-phase harmonic filter was used to compensate harmonics generated by non-linear load (electro static precipitator and variable speed driver that derives the fan). The instantaneous harmonic reduction theory that uses Fourier series was used to design the harmonic filter. Power SIMulation (PSIM) and MATLAB have verified the harmonic distortion and the active filter control scheme.

Keywords: Electro Static Precipitator (ESP), Harmonic Filter (HF), Total Harmonic Distortion (THD), Variable Speed Drive (VSD).

I. INTRODUCTION

The importance of ESP system is its high efficiency in removing the dust and gases from the cement plants [1][2]. Al-Tahady ESP had been designed and manufactured as a prototype to make further experiments and operations on this system. Iraq has a lot of cement plants and they emit a lot of pollutants to the environment. Figure (1) shows Al-Tahady ESP prototype as an experimental system, while figure (2) represents the DC power supply for ESP and variable speed driver for the fan respectively.

Power electronic circuits have become the need of the hour and find widespread applications due to their cost, less bulkiness, space requirement, and faster control possibility [3][4]. Their inherent problem is harmonics which is to be looked into with serious concern when considering the power quality of the system. Harmonics cause a serious impact on the quality of power by distortions and undesirable losses [5]. Further they cause the mal-operation of equipment because of the disturbance from ideal conditions. Several techniques can be used to mitigate harmonics.

The most commons are [6]:

1. Line Reactors
2. Passive Filters
3. DC Chokes
4. Active Filters
5. Multi Pulse drives

(a) 12 Pulse Drives

(b) 18 Pulse Drives

Design a harmonic filter was used to draw purely sinusoidal currents from the distribution network, but this is no longer the case with this new generation of receivers that take advantage of all the recent advances and improvements in power electronics. These power electronics systems such as variable speed drives offer non-linear characteristics. Some of the small power domestic electrical appliances supplies also draw very distorted currents. These non-linear loads lead to generation of current/voltage harmonics and draw reactive power and becoming troublesome problems in ac power lines [7].

Harmonics effects in power systems result is increased heating in the equipment and conductors, misfiring in variable speed drives, torque pulsation in motors, low system efficiency, and poor power factor [8]. It also causes disturbance to ESP and interference in nearby communication networks. The effect of this non-linearity could become sizeable over the next few years.

Hence it is very important to overcome these undesirable features by using harmonic filter to eliminate the total harmonic distortion and maintain it to acceptable level [9]. Harmonic filter have been considered as a possible solution for reducing current harmonics and also minimizing of power loses while transmission of energy from source to load. Active filter avoid the disadvantages of passive filters by using a switch mode power electronic converter to supply harmonic currents equal to those in the load currents [10].

Active filter can also compensate the load power factor [11]. In this way, the power distribution system sees the non-linear load and the harmonic filter as an ideal resistor. The

harmonic filter based on the current-controlled voltage source type Pulse Width Modulation (PWM) converter has proved to be effective even when the load is highly non-linear [12].



Figure 1: AI-Tahady ESP Prototype System

Active filters are highly accurate by control and monitoring, flexible harmonic control where system can grow as customer's needs change [13]. The benefits of active harmonic filters are:

- Shunt design cannot be overloaded
- Cancels 2nd-50th harmonic
- Provides 50 Hz reactive current
- Fast response to varying loads
- Expandable



Figure 2: (a) DC Power Supply for ESP, (b) Fan Variable Speed Driver, (c) The main control panel of ESP

While disadvantages can be summarized by

- Typically more expensive than other methods. More competitive where redundant VSD's are used.
- Large size
- More complex

The rest of this paper is arranged as, section 2, 3 and 4 presents an overview of ESP, VSD and AI-Tahady ESP system respectively. In section 5, a background theory will be reviewed and the harmonic filter design. Simulation results are given in sections 6 and 7. The paper is concluded in section 8.

II. ELECTRO STATIC PRECIPITATOR

Electro Static Precipitator (EP or ESP) is widely used in coal-fired power plant and other industries, like cement mill, steel mill, pulp and paper mill as the device of particulate pollution control [14].

A Transformer/Rectifier set (T/R set) is used to convert an input of 50/60 Hz alternative current at low voltage (typically 220~480V) into an output of Direct Current (DC), at high voltage (typically 30~100KV), in order to generate the corona effect on the Discharge Electrode (DE) from which the electrons are emitted to bombard the particles suspended in the flue gas. Figure 3 shows the circuit diagram of T/R set of the ESP.

After certain treatment time the particles carry sufficient negative charges and then are moved toward the grounded Collecting Electrode (CE) due to the electrical field constituted between DE and CE [15].

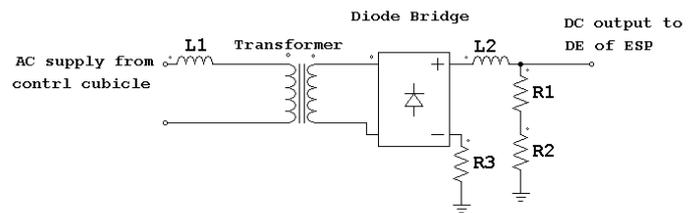


Figure 3: Circuit Diagram of T/R Set

The occurrence of a spark between DE and CE or ground is inevitable due to the limited dielectric strength between them and various conditions during operation. It is known that the particulate collection process will be terminated during sparks resulting in the temporary degradation of collection effectiveness of the ESP.

Other damages caused by sparks can also be seen from time to time in fields but such damages are easily overlooked or mistaken as being caused by other problems. Therefore, it is essential to understand the nature of a spark and its effect on an ESP. The clearness operation of the ESP is shown in Figure 4.

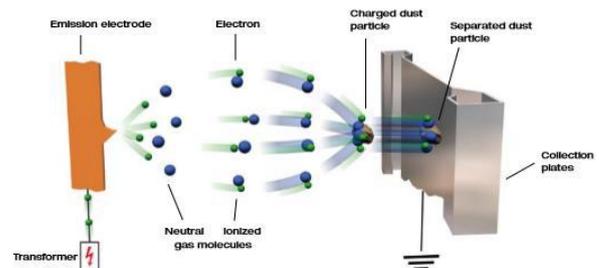


Figure 4: Clearness air process inside ESP [6]

III. VARIABLE SPEED DRIVE

A device used to control the mechanical power of the different machines involved in the process. Material treatment can also be controlled by VSDs [16]. A good example is a drying kiln, in which the hot air temperature must be constant. The process is controlled by controlling the speed of the hot air fans using VSDs.

Variable speed drives plays an important role in the oil and gas industry where high reliability is requested for subsea applications. Normally VSDs are placed on the platform and it is connected to the subsea load through a long cable [17]. Figure 5 show variable speed drive model.

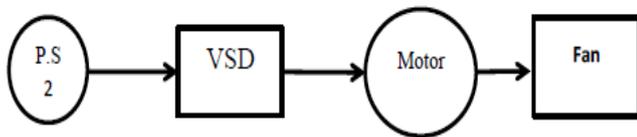


Figure 5: Fan VSD system model

IV. ELECTRO STATIC PRECIPITATOR

Both VSD and ESP have been connected in parallel with power supply. This caused a disturbance in the ESP system increasing the number of sparks. The non-linear load of VSD caused by thyristor and therefor-harmonic filter will be used for this model as shown in Figure 6.

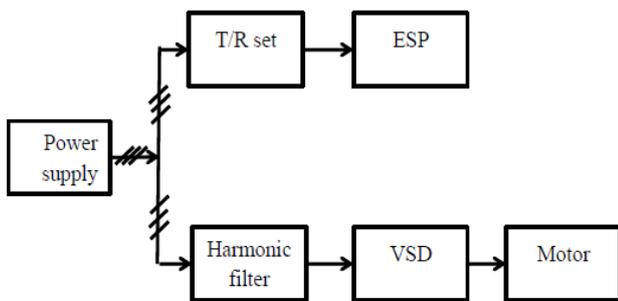


Figure 6: Al-Tahady ESP System Model With Harmonic Filter

In Al -Tahady ESP system there is a problem that ESP does not work properly because of VSD (non-linear load from thyristor). The solution for this problem is firstly done by separation of the power supplies meaning that the power supply to ESP is different from that supply to VSD or secondly by simulation adding harmonic filter before VSD as shown in figure (6). The power of the motor that used to drive the fan was 15 KW and the VSD model was (SV15OIGSA-4).

V. BACKGROUND THEORY

Unwanted harmonics in the AC signals generated by new drivers can be expressed as [12].

5.1 Bipolar output voltage notches

A pair of unwanted harmonics at the output of single-phase inverters can be eliminated by introducing a pair of symmetrically placed bipolar voltage notches as shown in figure 7.

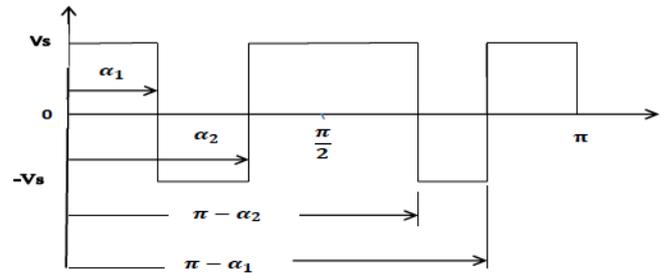


Figure 7: Output Voltage with Two Bipolar Notches per Half -Wave

The Fourier series of output voltage can be expressed as [18]

$$v_o = \sum_{n=1,2,3,\dots}^{\infty} B_n \sin n\omega t \tag{1}$$

The coefficients of the Fourier series (B_n) can be found from

$$B_n = \frac{4V_s}{\pi} \frac{1 - 2 \cos n\alpha_1 + 2 \cos n\alpha_2}{n} \tag{2}$$

Equation (2) can be extended to m notches per quarter-wave:

$$B_n = \frac{4V_s}{\pi n} (-2 \cos n\alpha_1 + 2 \cos n\alpha_2 - 2 \cos n\alpha_3 + 2 \cos n\alpha_3 - \dots) \tag{3}$$

$$B_n = \frac{4V_s}{\pi n} [1 + 2 \sum_{k=1}^m (-1)^k \cos(n\alpha_k)] \tag{4}$$

for $n = 1, 2, 3, \dots$

Where $\alpha_1 < \alpha_2 < \dots < \alpha_k < \frac{\pi}{2}$

The third and fifth harmonics would be eliminated if $B_3 = B_5 = 0$ and (2) gives the necessary equation to be solved.

$$1 - 2 \cos 3\alpha_1 + 2 \cos 3\alpha_2 = 0 \text{ or}$$

$$\alpha_2 = \frac{1}{3} \cos^{-1}(\cos 3\alpha_1 - 0.5) \tag{5}$$

$$1 - 2 \cos 5\alpha_1 + 2 \cos 5\alpha_2 = 0 \text{ or}$$

$$\alpha_1 = \frac{1}{5} \cos^{-1}(\cos 5\alpha_2 - 0.5) \tag{6}$$

These equations can be solve iteratively by initially assuming that $\alpha_1 = 0$ and repeat-ing the calculation for α_1 and α_2 . The result is $\alpha_1 = 23.62^\circ$ and $\alpha_2 = 33.3^\circ$.

5.2 Unipolar output voltage notches

With unipolar voltage notches as shown in Figure 8.

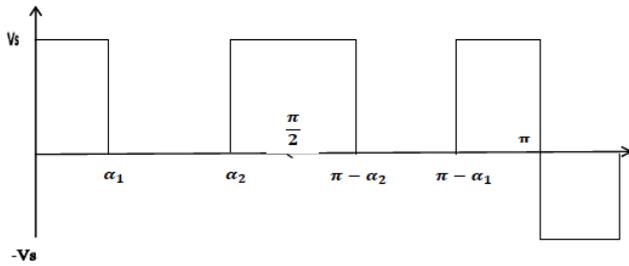


Figure 8: Unipolar Output with Two Notches per Half- Cycle

The coefficient B_n is given in (2)

Equation (5) can be extended to m notches per quarter-wave as (4). The third and fifth harmonics would be eliminated as shown in (5) and (6). These equations can be solve iterations using Mathcad program, we get $\alpha_1 = 17.83^\circ$ and $\alpha_2 = 37.97^\circ$. To find the load current output

1. Find X_L and X_C for a given model

$$X_L = \omega L \text{ AND } X_C = \frac{1}{\omega c} \quad (7)$$

Where $\omega = 2\pi n f$ and n =order of the harmonic

2. Find impedance for n th harmonic voltage where

$$|Z_n| = \left[R^2 + \left(X_L n - \frac{X_C}{n} \right)^2 \right]^{\frac{1}{2}} \quad (8)$$

3. Find power factor angle for n th harmonic voltage where

$$\theta_n = \tan^{-1} \left(\frac{X_L n - \frac{X_C}{n}}{R} \right) \quad (9)$$

The Fourier series of output voltage can be express in (1)

The coefficients of the Fourier series (B_n) can be found from eq (2). Dividing the output voltage by the load impedance and considering the appropriate delay due to the PF angle give the load current as

$$i_o(t) = \sum_{n=1,2,3,\dots}^{\infty} \frac{v_o(n)}{|Z_n|} \sin(\omega_o t - \theta_n) \quad (10)$$

Where $\omega_o = 2\pi f$

VI. HARMONIC FILTER DESIGN

The single-phase full bridge inverter in figure (9) supplies a load $R=10 \Omega$, $L=31.5 \text{ mH}$, and $C=112 \mu\text{f}$. The DC input voltage is $V_s=220 \text{ v}$ and the inverter frequency is $f_s = 60 \text{ Hz}$. The Output voltage has two notches such that third and fifth harmonics are eliminate to determine the expression for the load current $i_o(t)$ and to find an output C

filter is used to eliminate seventh and higher order harmonics, determine the filter capacitance C_c .

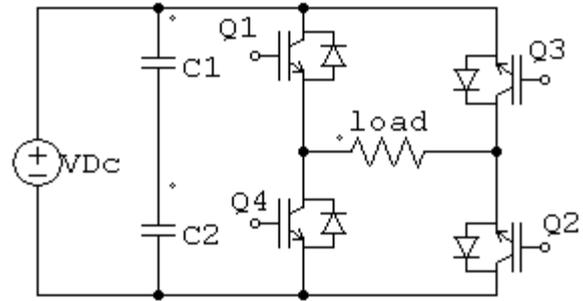


Figure 9: Single Phase Full Bridge Inverter

The output voltage waveform is shown in Figure 7 $V_s=220 \text{ v}$, $f_s = 60 \text{ Hz}$, $R=10 \Omega$, $L=31.5 \text{ mH}$, and $c=112 \mu\text{f}$, $\omega_o = 2\pi \times 60 = 337 \text{ rad/s}$.

The inductive reactance for n th harmonics voltage is $X_L = \omega L n = j2n\pi \times 60 \times 31.5 \times 10^{-3} = j11.87n \Omega$

The capacitive reactance for n th harmonics voltage is

$$X_C = \frac{1}{\omega c} = \frac{j10^6}{2n\pi \times 60 \times 112} = \frac{j23.68}{n} \Omega$$

The impedance for n^{th} harmonic voltage is

$$|Z_n| = \left[R^2 + \left(X_L n - \frac{X_C}{n} \right)^2 \right]^{\frac{1}{2}}$$

$$|Z_n| = \left[10^2 + \left(11.87n - \frac{23.68}{n} \right)^2 \right]^{\frac{1}{2}}$$

The power factor angle for n th harmonic voltage is

$$\theta_n = \tan^{-1} \left(\frac{X_L n - \frac{X_C}{n}}{R} \right) = \tan^{-1} \left(\frac{11.87n - \frac{23.68}{n}}{10} \right)$$

Equation (2) gives the coefficients of Fourier series,

$$B_n = \frac{4V_s}{\pi} \frac{1 - 2 \cos n\alpha_1 + 2 \cos n\alpha_2}{n}$$

The third and fifth harmonics would be absent form eq. (1) the instantaneous output voltage can be expressed as

$$v_o(t) = 235.1 \sin 337t + 69.4 \sin(7 \times 337t) + 114.58 \sin(9 \times 337t) + \dots$$

Dividing the output voltage by the load impedance and considering the appropriate delay due to the PF angle give the load current as

$$i_c(t) = 15.19 \sin(377t + 49.74^\circ) + 0.86 \sin(7 \times 377t - 82.85^\circ) + 1.09 \sin(9 \times 377t - 84.52^\circ) + \dots$$

The nth higher order harmonics would be reduced significantly if the filter impedance is much smaller than that of the load, and a ratio of 1:10 is normally adequate.

$$Z_n = 10X_e$$

Where the filter impedance $X_e = \frac{1}{377nC_e}$

The value of filter capacitance C_e can be found from

$$\left[10^2 + \left(11.87n - \frac{23.68}{n} \right)^2 \right]^{\frac{1}{2}} = \frac{10}{377nC_e}$$

For the seventh harmonic, $n=7$ and $C_e = 47.3 \mu f$.

Depending on the previous analysis Figure 10 illustrates a harmonic filter used to eliminate the harmonics generated by semiconductors.

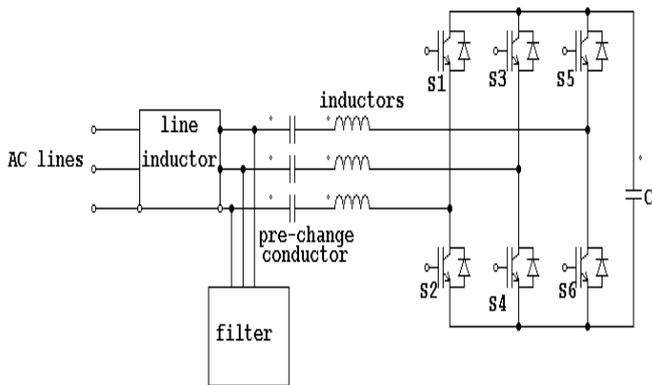
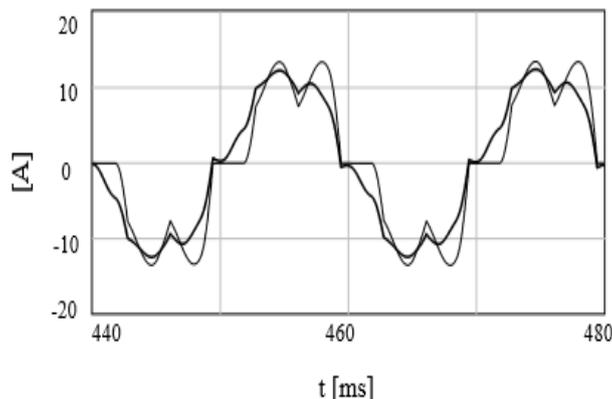
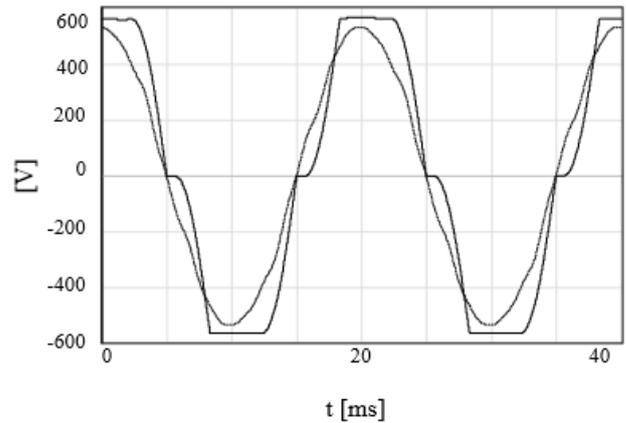


Figure 10: Circuit Diagram of Active Filter by Using PSIM

The output waveform of active harmonic filter is shown in Figure 11.



(a)



(b)

Figure 11: Waveform Before and After Filtration (a) Current Waveform (b) Voltage Waveform

VII. SIMULATION USING MAT LAB

Now simulation of the conditions before and after the application of harmonic filters and observing the effectiveness of filter design. Different harmonics can be considered as different current sources superimposed on each other. There will be two simulations; one before filtration (Figures 12, 13 and 14) and one after filtration (Figures 15 and 16).

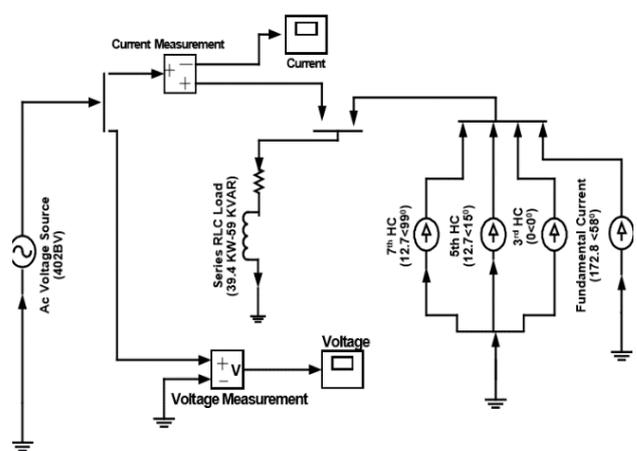


Figure 12: Simulations without harmonic filter

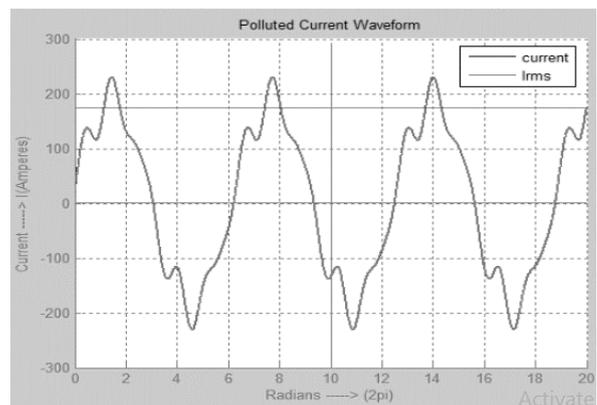


Figure 13: Simulation of Polluted Current Circuit without Filtration

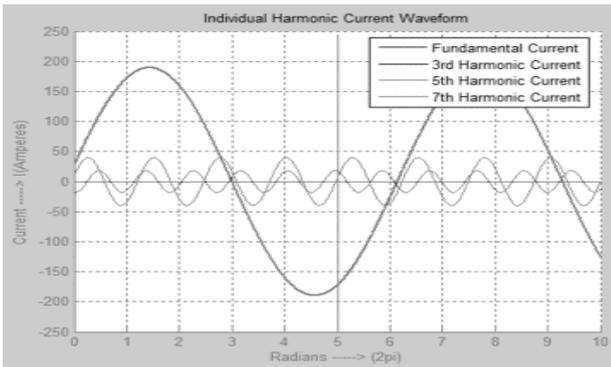


Figure 14: Simulation of harmonic components

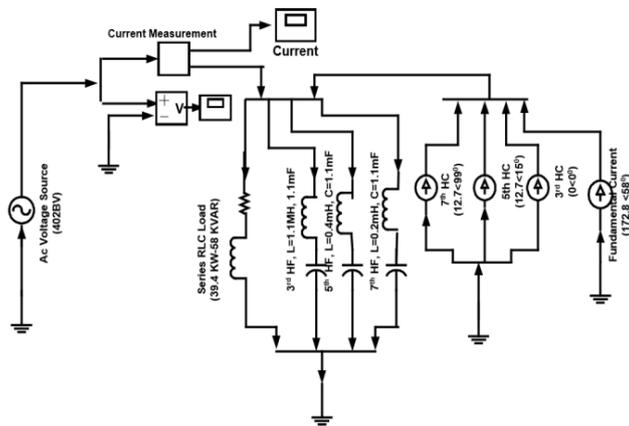


Figure 15: Simulation of Circuit with Filters

VIII. SIMULATION USING PSIM

According to configuration the Active filter classified into Series, shunt, and hybrid active filter. Among all configuration shunt active filter is superior for reduction of current harmonics present in the system. Figure (16) presents the shunt active filter topology based on a three phase voltage source, using IGBT switches, connected in parallel with the AC three-phase three-wire system through three inductors and PI controller to control the system.

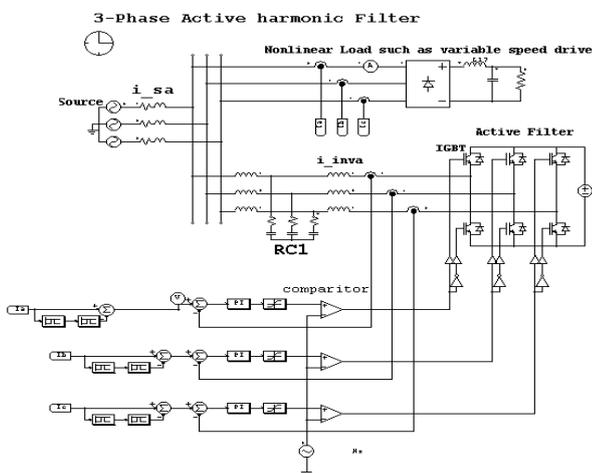
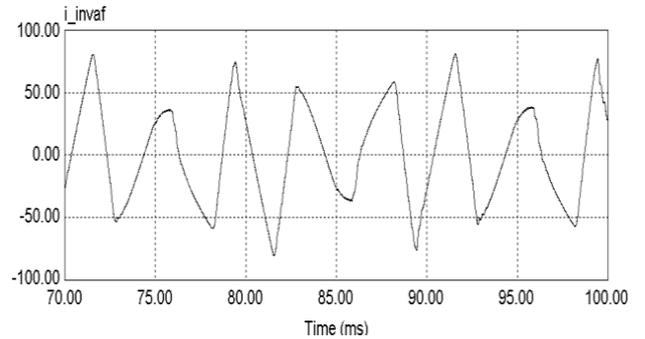
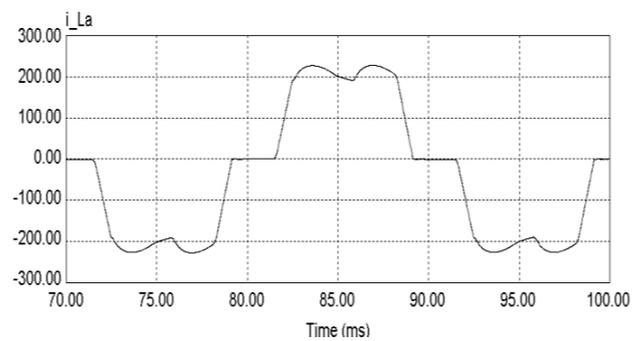


Figure 16: Active Harmonic Filter

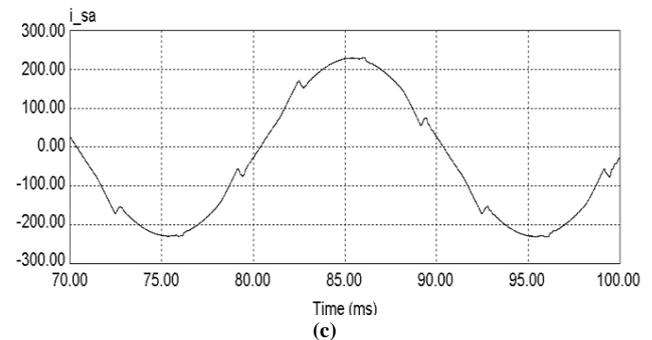
The results of above simulation are shown in Figure 17.



(a)



(b)



(c)

Figure 17: (a) The current Output of Inverter (b) The Load Current (c) The Source Current after Apply Active Harmonic Filter

From the above results at the fig. 17 (a), the current output from inverter was very distributed that prove the inverter is a non-linear device and it produced a harmonic to the system. The output current from load was also disturbed because of the load inductor that produced a harmonic. The output current of source after filtration is pure because of adding filter that have a capacitor, which improves power factor and correct the wave.

IX. CONCLUSIONS

The wide spread utilization of power electronic devices has significantly increased the number of harmonic generating apparatus in the power systems. This harmonics cause

distortions of the voltage and current waveforms that have adverse effects on electrical equipment. This harmonics effect on power systems can be summarized as increase losses of devices, equipment heating and loss-of-life, and interference with protection, control and communication circuits as well as customer loads.

Harmonics are one of the major power quality concerns. The estimation of harmonic from nonlinear loads is the first step in a harmonic analysis and this may not be straightforward task. To eliminate this situation, the harmonic study analysis becomes an important and necessary task for engineers. Harmonic filter is used for eliminating the total harmonic distortion and maintain it to acceptable level.

ACKNOWLEDGMENT

The authors would like to express their thanks to the Electrical Engineering Dept. at Mosul University Especially Dr. Mohammed. O. Mustafa and Dr. Omer shrif Al deen for their help and support. Thanks also go to the R&D department at Al-Zawraa state company (AL Tahady) for their assistance and cooperation.

REFERENCES

- [1] A.Cantini, L. Leoni, F. De Carlo, M. Salvio, C. Martini, and F. Martini, "Technological energy efficiency improvements in cement industries," *Sustain.*, vol. 13, no. 7, 2021, doi: 10.3390/su13073810.
- [2] S. Rampuri, "Study and Analysis of Occupational & Health Diseases in Cement Industries," *Int. J. Adv. Res. Dev.*, vol. 2, pp. 1–7, 2017, [Online]. Available: www.ijarnd.com
- [3] B. K. Bose, "Power Electronics in Smart Grid and Renewable Energy Systems," *Proc. IEEE*, vol. 105, no. 11, pp. 2007–2010, 2017, doi: 10.1109/JPROC.2017.2752538.
- [4] O. Krishan and S. Suhag, "An updated review of energy storage systems: Classification and applications in distributed generation power systems incorporating renewable energy resources," *Int. J. Energy Res.*, vol. 43, no. 12, pp. 6171–6210, 2019, doi: 10.1002/er.4285.
- [5] M. Bajaj and A. K. Singh, "Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques," *Int. J. Energy Res.*, vol. 44, no. 1, pp. 26–69, 2020, doi: 10.1002/er.4847.
- [6] L. E. Elkraft, "Variable Frequency Drives and Harmonic Abatement Techniques," *IEEE-500*, 2010, [Online]. Available: www.ijsr.net
- [7] B. Singh and R. Singh, "Design of Shunt Active Power Filter to Eliminate Harmonics Generated by CFL," *Int. J. Recent Res. Electr. Electron. Eng.*, vol. 2, no. 3, pp. 55–62, 2015.
- [8] Y. Asadi, M. Eskandari, M. Mansouri, S. Chaharmahali, M. H. Moradi, and M. S. Tahriri, "Adaptive Neural Network for a Stabilizing Shunt Active Power Filter in Distorted Weak Grids," *Appl. Sci.*, vol. 12, no. 16, 2022, doi: 10.3390/app12168060.
- [9] A.F. Zobaa and S. H. E. Abdel Aleem, "A new approach for harmonic distortion minimization in power systems supplying nonlinear loads," *IEEE Trans. Ind. Informatics*, vol. 10, no. 2, pp. 1401–1412, 2014, doi: 10.1109/TII.2014.2307196.
- [10] L. A. Morân, "A simple and low-cost control strategy for active power filters connected in cascade," *IEEE Trans. Ind. Electron.*, vol. 44, no. 5, pp. 621–629, 1997, doi: 10.1109/41.633456.
- [11] E. P. Engineering, "Design and Simulation of Active Harmonic Filter for Reducing Harmonic Distortion and Improving Power Factor in Industrial Load," vol. 03, no. 10, pp. 1934–1940, 2014.
- [12] B. Singh, K. Al-haddad, S. Member, and A. Chandra, "A Review of Active Filters for Power Quality Improvement Bhim," October, vol. 46, no. 5, pp. 960–971, 1999.
- [13] I.Colak, E. Kabalci, G. Fulli, and S. Lazarou, "A survey on the contributions of power electronics to smart grid systems," *Renew. Sustain. Energy Rev.*, vol. 47, no. 1, pp. 562–579, 2015, doi: 10.1016/j.rser.2015.03.031.
- [14] P. Asia, "The Evolution of Emissions Control Technologies to Meet Lower Limits," 2017.
- [15] C. E. Division, "Spark and Its Effect on Electrostatic Precipitator," no. June, pp. 1–12, 2006.
- [16] A.T. De Almeida, F. J. T. E. Ferreira, and D. Both, "Technical and economical considerations in the application of variable speed drives with electric motor systems," *Conf. Rec. Ind. Commer. Power Syst. Tech. Conf.*, vol. 41, no. 1, pp. 136–144, 2004, doi: 10.1109/icps.2004.1314992.
- [17] B. Monsen, K. S. Rongve, T. Laegreid, and C. Gutscher, "Åsgard Subsea Gas Compression-Technology Qualification Testing With High-Speed Vsd and Very Long Step-Out Cable," *IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 1552–1561, 2014, doi: 10.1109/TIA.2013.2293912.
- [18] M. H. Rashid, *Power Electronics Devices, Circuits & Applications*, 4th Edition. 2014.

Citation of this Article:

Taha N. DeKheel, Mohammed O. Mustafa, Mehdi J. Marie, “Design of Harmonic Filter for AL-Tahady Electro Static Precipitator System” Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 8, Issue 2, pp 88-95, February 2024. Article DOI <https://doi.org/10.47001/IRJIET/2024.802013>
