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Harmonics compensation in industrial power network using Hybrid Active Power Filter (HAPF) in d-q frame

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Abstract: In AC power networks, the use of harmonic and reactive power compensations through active power filters has become emerging aspect of today's commercial market. With the advancement of new technologies, loads based on power electronics are regularly being used in low and medium voltage distribution systems, which eventually cause the harmonics in the system currents and voltages. The most dangerous harmonics are the later i-e, 3rd , 5th , 7th and so on, which are basically result of current harmonics. They cause degradation in the performance and working of other important power system equipment. In order to mitigate these daunting harmonics, the best option is to use the hybrid power filters which combine the characteristics of both active and passive harmonic filters al-together.

The main idea of this research is to model an industrial network and to perform an analysis over the Total Harmonic Distortion (THD) in the power system. The use of Hybrid Active Power (HAPF) kept the THD value well below 8%, as recommended by European Standard EN50160. With the implementation of HAPF, an additional advantage of power factor improvement was also achieved. PQ theorem was used for calculating parameters of hysteresis control used for filter implementation. Results presented in the research paper confirm the efficiency of designed filter because the THDs of both voltage and current were restricted to 2% and the system power factor was improved too. The major contribution of this research is that power quality was improved most economically using P-Q technique through HAPF.

Keywords: Hybrid Active Power Filter (HAPF), EN 50160 standard, Power Quality, Total Harmonic Distortion (THD), Harmonics

1. INTRODUCTION

Due to the increasing practice of non-ohmic devices, either in residential or industrial applications, distribution networks have been contaminated with adverse harmonics. These harmonics eventually lead to distortion in current and voltage waveforms and were also responsible for other side effects such as electromagnetic interference (EMI), increased losses and capacitor botch. For specific load category, the EN 50160 standard confines the all-out sum of harmonics that a supply system is able to tolerate. According to EN 50160 standard, the THD of system voltage counting harmonics up to order of 40 should be less than or equal to 8% (Masetti *et al*.2010). Thus the filters are very much essential for the harmonic mitigation and improving the system power quality, thereby increasing the reliability of the distribution system.

Among the various practical solutions for improving the power quality of distribution network, the Hybrid Active Power Filters (HAPFs), having benefits of both active and passive filters, have become the key technology to compensate the current and voltage harmonics in distribution networks (Zobaa, *et al.* 2014). Passive filters applied in HAPFs are used to compensate 5th and 7th harmonics (Phipps et al.1994), which are major source of disturbance in system's power quality. The active power filters are responsible for better performance of power system and they are proved to be the most economical solution. For the reason of improving the power quality the main advantages of HAPFs are their exclusion of current harmonics, mitigation of reactive power, and the regulation of system voltage. Along with power quality enhancement, the HAPF design also improves the power factor of industrial network, which was analyzed via Simulink results. The advantage of high power factor is that the load current slightly decreases and load voltage increases by small percentage, which is the actual need of industrial customers.

The THD is the most common assessing index for harmonically distorted waveforms (IEEE 519-92, *et. al.* 1992). It is well-explained as the squaring ratio of harmonic components to the fundamental frequency. Voltage THD considers the first forty harmonics and is given by (1):

$$THDU = \sqrt{\sum_{2}40\left(\frac{U_h}{U_1}\right)^2} \times 100 \qquad (1)$$

where: U_h is amplitude of voltage harmonic and U_1 is fundamental amplitude.

The THD expressed in percentage is mostly used to differentiate various utility networks. EN 50160 declares the harmonics content of 8% THD as a satisfactory maximal value and any assessment violating it would be intolerable.

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This research focuses on the analysis of dynamic and steady state characteristics of HAPFs for compensating harmonics caused by industrial furnace. The propositions are modeled and analyzed through MATLAB Simulink software. The proposed HAPF design, restricts the harmonics level in industrial network to about 2% for both voltage and current using HAPF. The power quality was improved most economically using P-Q technique.

2. POWER QUALITY ISSUES AND ITS MITIGATION

According to different international standards, power quality is actually the physical characteristics of utility network which specifies the deviations in system parameters under the normal operating conditions. Any power issue exhibited in voltage, current or frequency variations, which may cause failure or malfunction of utility equipment, is considered as power quality issue. Though it has been found that power quality of industrial network is basically voltage quality and it may affect the system reliability. Failure of any equipment due to voltage deviations is actually voltage quality issue. Ability to supply the load, to withstand unexpected disturbances like faults and to consider especially over-long power interruptions, all of them are characterized by the system reliability (Rahmani *et al.* 2014).

In industrial processes entire manufacturing panels would be out of order if supply to that industry is highly distorted, thus causing risky condition for workers and also wastage of costly product. Damage to industrial units in a big multinational firm may cause loss of hundreds of irretrievable Euros per second of shut down and also plenty much time is required for recovery of processes. Increased practice of different power electronic devices to assist the heavy and expensive industrial processes has created the big issue of power quality, especially when supplying arc furnaces through bridge rectifiers (Pomilio *et al.* 2007). The knowledge of power quality and the approach to handle it is a worry for distribution companies and power customers.

Two prominent solutions are available for power quality issues. The number one is the load conditioning (Grady *et al.* 1990), it assures that working device is less affected by power system instabilities and allows the equipment to operate even during the substantial voltage fluctuations. The second one is the use of harmonic filters, which have proved to be an efficient and practical solution to power quality issues. Mitigation of harmonics is to create their way to ground or to restrict them, not to enter into power system by using some active and passive electrical and electronic circuits – which are commonly called harmonic filters (Akagi *et al.* 1996).

3. FILTERS AND THEIR USE

Filters designed with use of resistors, capacitors and inductors are called passive filters (Akagi *et al.*1996). The capacitive reactance and inductive reactance are frequency dependent, so any grouping of R, L and C elements may be made to pass or block certain range of frequencies. The mitigation of system harmonics through passive filters has proved to be practical and cost effective approach due to its simplicity, low cost and reliable operation. Limited bandwidth, increased losses, big size and swinging at tuned frequency are some common disadvantages of passive filters. Power factor improvement can also be achieved with use of capacitive passive filtering circuit. Keeping in view the source impedance, the passive filters are coupled in shunt or series to achieve the resonance.

The circuits using transistors and operational amplifiers along with passive filters are called active filters (Akagi *et al.* 1996). With the advancement of power electronics combinations are arranged to generate such negative currents that are in counter-phase with current harmonics to mitigate the effects of harmonics in industrial networks. Active filters are actively able to compensate harmonics' distortion in both current and voltage signals. With the use of power electronics, active filters may control the harmonics compensation and can easily be retuned with changing states (Biricik *et. al.* 2016) if power system contains passive filters which are sensitive to frequency. However the high cost, circuit complexity, instability and component sizing are some disadvantages of active filters. Keeping in view the merits and demerits of active and passive power filters, one can design such a circuit that has the benefits of both active and passive filters so as to assure most effective compensation to harmonics. Such circuits are called hybrid filters. The design of harmonic filters should satisfy the basic requirements of power system, so as to achieve stable and distortion-free operation of power network.

4. MODELING OF HYBRID ACTIVE POWER FILTER

Active filters are incorporated with passive filters to improve their mitigation characteristics and performance efficiency. The industrial approach to connect active with passive filters in the series combination is shown in **(Fig. 1.a. Fig.1.b)** shows the internal model of induction furnace with twelve pulse rectifier. A coupling reactor has been used to avoid switching transients.

The three phase source voltage with magnitude of 415 volts and frequency of 50 hertz is modeled to supply industrial network installed with arc furnace of 14 ohms resistance and 0.1 mili-henries inductance, supplied through bridge rectifier. Hysteresis controlled technique has been applied for generating switching signals for active power filter. The Proportional Integral (PI) controller is responsible for maintaining the voltage of DC bus which is normally greater than the source voltage. The designed scheme is consisted of double tuned passive filter which is responsible for mitigation of 5th and 7th harmonics of currents.

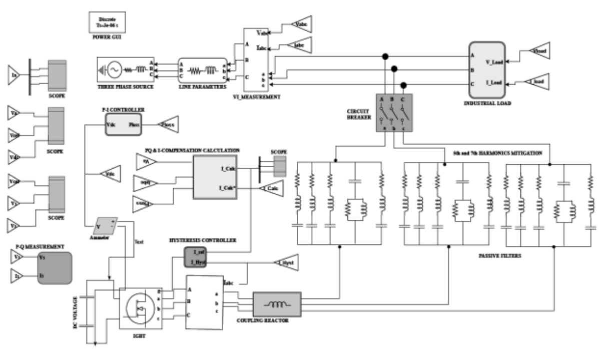

Fig. 1.a. Simulink model for industrial power circuit with complete HAPF

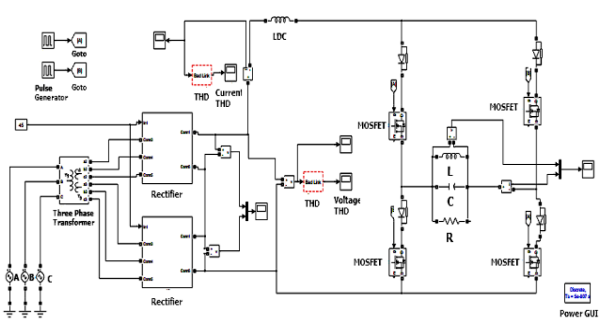

Fig. 1.b. Simulink model for 12-pulse Industrial induction furnace

Table 1. System parameters and values

System Parameters	Designated Values
Source voltage	415 V at 50 Hz
Capacitance of DC bus	4600 μF
DC capacitor reference voltage	400 V
No-linear load	14.0 Ω and 0.10 mH
Source resistance and inductance	0.1 Ω and 1.08 mH
Passive filter	L_1= 13.50 mH, C_1 = 30 µF, R_1 = 0.0989 Ω
	$L_{r=}$ 6.75 mH, C_r= 50 µF, R_r= 0.1240 Ω

The complete description of the system's parameters and their specifications is given in (Table 1).

5. RESEARCH METHODOLOGY

5.1. PQ theorem for reference current estimation

The instantaneous power control technique for voltage source with piecewise functional blocks is shown in **(Fig. 2).** Harmonics are present into the circuit because of non-Ohmic loads. In PQ theorem, the three phase line currents and voltages are taken as input signals and hence reference currents are generated accordingly (Norani *et al.* 2007). With the resulting reference currents, the switching pulses are then generated that are basically used to trigger Insulated Gate Bipolar Transistor (IGBT) of active power filter. Based on reference currents, the capacitor would charge and discharge by triggering the active power filters.

The PQ theorem is analyzed on the basis of instantaneous power defined in the time domain. By using Clarke'sor (α-β) transformation, the three phase source voltages (V_a, V_b, V_c) and currents (I_a, I_b, I_c) are transmuted into discrete coordinate system components (V_α. V_β, V_0) and (I_α, I_β, I_0) respectively according to the instant active and reactive power components (Shuai, *et al.* 2011). The result of this transmutation is the projection of the system parameters onto the reference frame of two stationary axes.

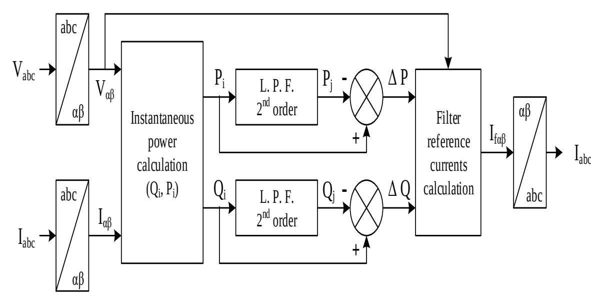

Fig. 2. Principle of PQ-theorem for Clarke's transformation.

Clarke's transformation for voltage quantities is given by (2):

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} \equiv \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{-2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2)$$

Correspondingly for distorted load currents Clarke's transformation is given by (3):

$$\begin{bmatrix} I_\alpha \\ I_\beta \\ I_0 \end{bmatrix} \equiv \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{-2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (3)$$

According to PQ theorem, the instantaneous real power can be found through (4):

$$P(t) \equiv V_a I_a + V_b I_b + V_c I_c \tag{4}$$

The instant real power in reference frame of two stationary axes is arranged by (5) and (6):

$$P(t) \equiv V_\alpha I_\alpha + V_\beta I_\beta \tag{5}$$

$$P_0(t) \equiv V_0 I_0 \tag{6}$$

where: *P(t)* is the instant real power, $P_0(t)$ is instant homo-polar sequence power. Likewise the instant reactive power can be agreed by (7) and (8):

$$Q(t) \equiv \frac{-1}{\sqrt{3}}[(V_a - V_b)I_c + (V_b - V_c)I_a + (V_c - V_a)I_b] \tag{7}$$

$$Q(t) \equiv V_\alpha I_\beta - V_\beta I_\alpha \tag{8}$$

The instantaneous real and reactive power in matrix format can be found by equation (9):

$$\begin{bmatrix} P \\ Q \end{bmatrix} \equiv \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{9}$$

The harmonic constituents of load currents, after extricating the direct and alternating terms of instantaneous power can be found by utilizing inverse equation (10) for current *(I'_α and I'_β):*

$$\begin{bmatrix} I'_\alpha \\ I'_\beta \end{bmatrix} \equiv \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \nabla P \\ \nabla Q \end{bmatrix} \tag{10}$$

5.2. Gate signal generated through hysteresis control

The hysteresis control, involving current controlled technique, has been used in HAPF model for generating pulses to trigger IGBT Bridge and is demonstrated in Fig.1. Based on bang-bang method (Lam et al.2012), the hysteresis control generates pulses according to the reference current signals, so to facilitate the proper harmonic compensation. To drive the hysteresis controller, an error signal is generated by comparing compensation current with the reference current. Proposed hysteresis control is based on hysteresis band of 0.2 amperes with +0.1 and -0.1 as upper and lower boundaries respectively

5.3. Double tuned passive power filter design

1.1. The **PI Controller for upholding DC Bus Voltage**

Proportional and Integral (PI) controller was used for simulation work, upholding DC bus voltage persistent at a reference value. In this sub-system, feedback signal for PI controller is obtained from DC bus voltage of active power filter. Error signal for PI controller is generated by subtracting actual voltage from DC bus voltage. The output of PI controller is reference in-phase components.

1.2. Double tuned passive power filter design

The designed Hybrid Active Power Filter scheme contains passive filter circuitry connected in parallel with load to captivate the undesired system harmonics as shown in Fig.1. The most commercial categories of passive power filters are single tuned, double tuned and band pass filters (Ginn *et. al.* 2006). However for effective response, the double tuned filters were used in this research. An arrangement of double tuned 1st order filter based on *RLC* components is shown in Fig.1. In this double tuned passive filter, two resonant frequencies are achieved from current to mitigate the 5th and the 7th harmonic components as the most dominant in waveforms (Raghavendra *et. al.* 2017). The relation among *R*, *L*, *C* and *Q* elements to design different passive filters is given by (11), (12) and (13):

$$C_k \equiv 1/L_k\,(2\pi fr)^2 \tag{11}$$

$$R_k \equiv L_k(2\pi fr)/Q \tag{12}$$

$$Q \equiv R_k\sqrt{C_k/L_k} \tag{13}$$

where: f_r is resonant frequency, *k* is harmonics order, *Q* is quality parametric factor, R_k and L_k are the resistance and inductance of *k*-th harmonic filtering element respectively.

6. RESULTS AND DISCUSSION

To avoid harmonic distortion in industrial network, the HAPF has proved to be the most promising and effective technique and its efficacy is assured through simulation outcomes, discussed in this part of the paper. Fig.3 shows three phase load current waveforms of the designed industrial circuit without HAPF application. Since, extremely disturbed waveforms are evidently noticeable. By utilizing the Fast Fourier Transform (FFT) technique, the harmonic spectrum of current for industrial arc furnace is demonstrated in Fig.4, where THD content of 28.7325% can be noticed. It is well visible in Fig.3 and 4 that the most dominant harmonics content is the 5th, which is followed by the 7th

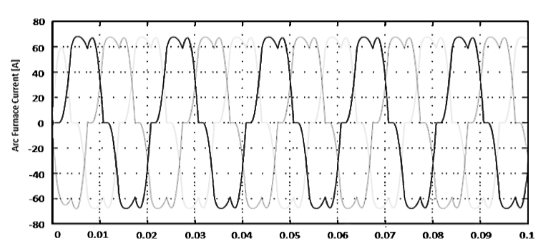

Fig.3. Load current waveform of simulated industrial network

For number of pulses (p) expected harmonic orders is given by:

$$H_k \equiv N\rho \pm 1 \tag{14}$$

where: H_k is harmonic order and N is constant.

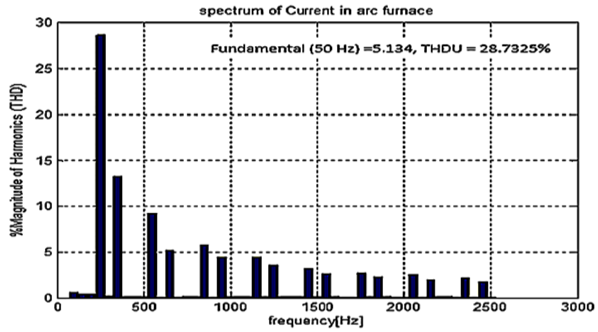

Fig. 4. Harmonic spectrum of load current of industrial network

For p = 6 and N = 1, 5th and 7th harmonics will be present and these harmonics contents will be effectively mitigated by designed double tuned passive filter. For N = 2, 11th and 13th harmonics will be present and with higher value of N, higher order of harmonics will be present. These higher harmonic contents can be compensated by the proposed active power filter. Therefore, harmonics which are multiplication of 3 such as 3rd, 9th, 15th and higher were compensated, which is confirmed by FFT spectrum in Fig. 4

Likewise harmonically distorted voltage waveform for arc furnace is illustrated in Fig.5 and its harmonic spectrum in Fig.6. it can be noticed that the voltage THD is 10.8626%, which is actually due to the presence of the 5th and the 7th harmonic. This assures that distorted currents caused by twelve-pulse level bride rectifier connected to arc furnace in industrial network are the origin for such voltage distortions. From above values, it can be seen that values of THD for both voltage and current are above the safe level of 8%, declared by EN 50160 standard. The harmonic filtering circuit is needed to harness these distortions.

The harmonic spectrums shown in Fig. 4 and 6 undoubtedly demanding to design a harmonic filter for compensating such harmonics and hence HAPF was recommended. Reference current was determined by utilizing PQ theorem in steady α-β axes in order to insert out-phase currents, generated by the designed HAPF which actually tracked the distorted arc furnace current in the industrial network, more effectively than another technique.

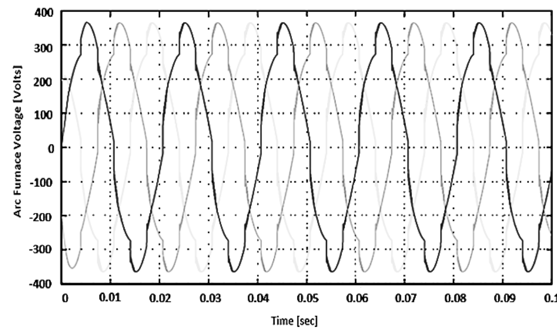

Fig. 5. Load voltage waveform of simulated industrial network.

Fig. 7 depicts HAPF's current exactly following the reference current, confirming the efficacy of designed power filter. After assigning the proper values to HAPF elements, control must be set aside to monitor the current injection to lessen the harmonic distortion and maintain the designated voltage at DC bus. Hysteresis control is used in this research due to its simplicity and easy implementation.

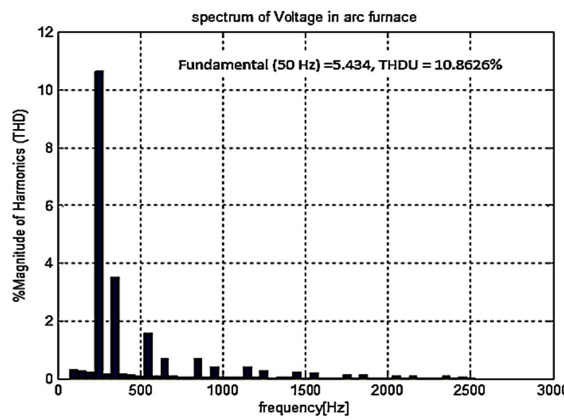

Fig. 6. Harmonic spectrum for load voltage of simulated industrial network

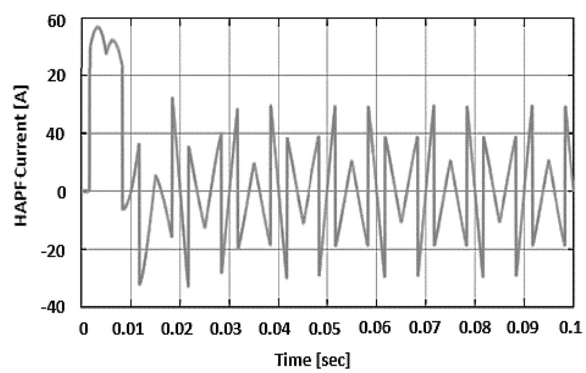

Fig. 7. HAPF current tracking the reference current

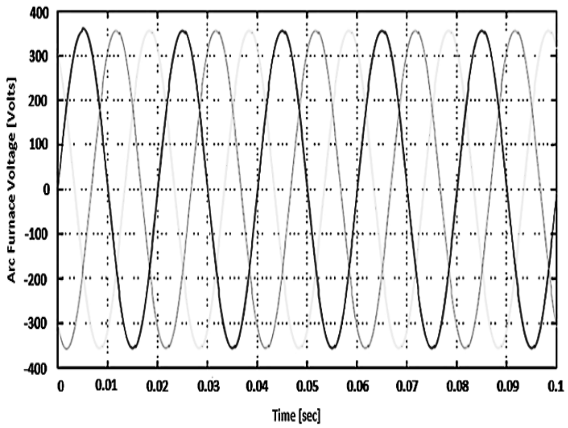

Fig. 8. Waveform of load current after implementing HAPF

Designed filter operated on hysteresis control technique has been analyzed to assure its efficiency for harmonic compensation in industrial network. Current waveform shown in Fig. 8 indicates the nearly pure sinusoidal signals. It has also been observed that voltage waveform illustrated in Fig. 9 has been improved tremendously. Thus it can be confirmed from Fig. 8 and 9 that power factor has been improved too, with decrement of load (arc furnace) current and enhancement of load voltage profile.

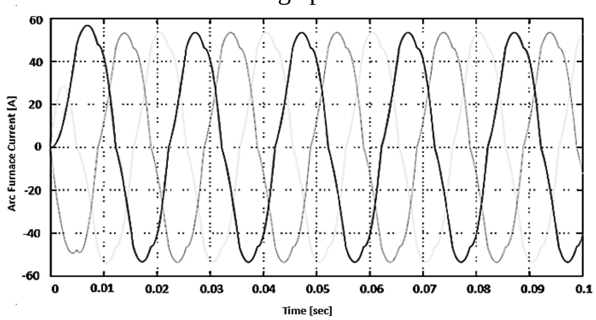

Fig. 9. Waveform of load voltage after implementing HAPF

Table. 2 Comparison of THDs of both current and voltage for different arc furnace resistances

Furnace Resistance (Ohms)	Current THD (%)		Voltage THD (%)	
	Before HAPF	After HAPF	Before HAPF	After HAPF
08	11.9873	1.9983	11.8143	1.9732
10	19.8143	2.2072	11.5173	1.6134
12	22.7345	2.3162	11.2363	1.4721
14	28.7325	2.4102	10.8626	1.3585

Table.2 gives the comparison of THD values for both current and voltage with and without proposed HAPF under different loading conditions. It is observed that the current harmonics increases as load resistance is increased whereas voltage THD is reduced. In both cases, the proposed HAPF mitigates the harmonics successfully for considered values resistances of arc furnace.

Harmonic spectrums shown in Fig. 10 and 11 confirm the THD values for both current and voltage are upgraded, which are now below the 8% limit.

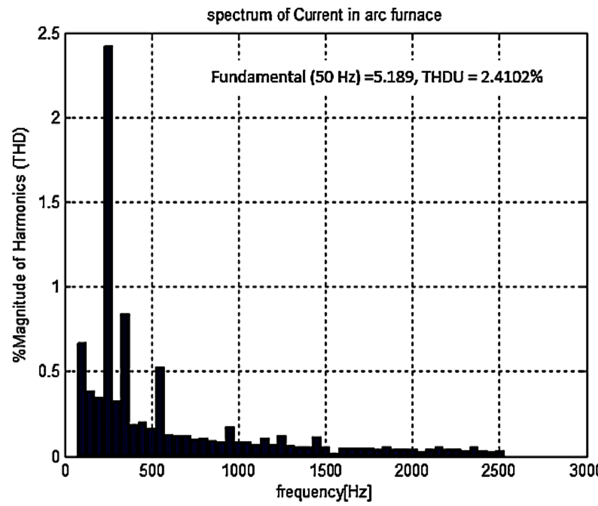

Fig. 10. Harmonic spectrum of industrial arc furnace after using HAPF

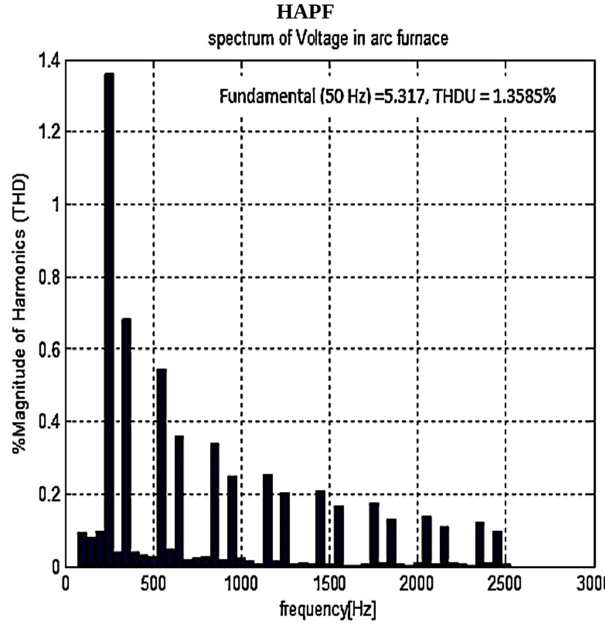

Fig. 11. Harmonic spectrum of voltage for industrial arc furnace after implementing HAPF

7. CONCLUSION

In modern power system, the increased use of non-linear loads and power electronic converters produces harmonics in system voltage and current signals. In industrial power networks, the biggest sources of voltage harmonics are adjustable speed drives and arc furnaces. The most promising solution for harmonics in industrial power system is proved to be the hybrid filtering technique which combines the benefits of both active and passive filters. In this research, with the help of MATLAB Simulink analysis, the results for Total Harmonic Distortions (THDs) for current and voltage were obtained and their values were 28.7325% and 10.8626% respectively before applying HAPF. The THDs values for both current and voltage were above prescribed limit of 8%, declared by EN 50160 standards. In order to compensate the distortions in current and voltage signals and to lessen the value of both THDs, the PQ theorem was applied through static frame of HAPF. These results confirmed the improvement of power factor too after using designed HAPF into the network. For maintaining voltage of DC bus, the Proportional-Integral controller was used. In order to control and inject HAPF circuitry smoothly into industrial network, the hysteresis control was applied. The efficiency of HAPF was confirmed via the THDs values for current and voltage signals, which were reduced to 2.4102% and 1.3585% respectively. The characteristics of industrial arc resistance with different resistances were analyzed to investigate the performance of HAPF for harmonics mitigation and it was proved to be satisfactory.

8. FUTURE RECOMMENDATIONS

Since the use of manual breakers has restricted the frequent application of HAPF into the network. HAPF itself contributes to the losses and causes the loading of network. In order to avoid this problem, the Hardware-in-Loop (HIL) based laboratory simulator should be used to acquire the real time results of Industrial Network at higher switching frequencies. It uses FPGA based controllers to handle out the injection of P-Q currents through HAP filters

9. ACKNOWLEDGEMENT

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