IMPLEMENTATION OF WAVELET TRANSFORM TECHNIQUE FOR DETECTION AND REDUCTION OF HARMONICS IN AN INDUCTION FURNACE

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Abstract- Power quality has become prime criteria in modern scenario of power system analysis. Today, non-linear loads make up a large percentage of all electrical demand. Non-linear loads draw current in short pulses during the peak of the line voltage. These non-sinusoidal current pulses introduce unanticipated reflective currents back into the power distribution system and these currents operate at frequencies other than the fundamental frequency. This investigation is mainly based on the issues relating to the power quality of induction furnace, as it is considered as one of the major non-linear loads among industries. Power quality analyzer is used at the installation of induction furnace to observe the harmonics generated by the electrical appliances. The Simulink model of induction furnace is developed in MATLAB based on the related schematic and wiring diagram of the installation. The possible implementation of passive filters is exhibited to reduce harmonics with the Simulink model of induction furnace. Wavelet transform technique is also implemented to mitigate the harmonics.

Index Terms- Daubechies, Harmonics, Induction furnace, Non-linear load, Passive filters, Power quality, Power quality analyzer, Wavelet transform.

I. INTRODUCTION

The term Power quality (PQ) is used to describe a wide range of electrical power measurement and operational issues. Organizations are more concerned with the importance of PQ because of potential safety, operational and economic impacts. Most of the loads connected in power distribution systems are considered as non-linear, where impedance changes with the applied voltage. The changing impedance indicates that the current drawn by the non-linear load will not be sinusoidal even when it is connected to a sinusoidal voltage. This significantly affects the quality of power supply, due to which the purity of the supply waveform is lost. This ends up exiting many PQ problems. Some of the PQ problems like electric noise, voltage surges, sags, interruptions, harmonics, transients, fluctuations and flicker present in a power line, cause serious problems to other electrical devices connected to that electrical system.

The induction process is one of the important methods in melting non-ferrous metals and iron in foundries. When an induction furnace is connected as a load at high production levels, it introduces more PQ problems. Under such circumstances, the furnace current is very large compared to the utility supply. Furnace generates large fluctuating load currents with fixed and variable frequency harmonics that lead to adverse interactions between the utility system and furnace [1]-[3]. Power quality analyzer (PQA) is used to detect and classify PQ disturbances generated by these furnaces. They also help to determine the amount of compensation required to suppress harmonics and correct the voltage variations like overvoltage, under voltage, spikes and impulses.

Normally PQ problems are mitigated using suitable passive filters. The analysis of different PQ problems can also be done simultaneously in both time and frequency domains using Wavelet transform (WT), where multi-resolution signal decomposition provides valuable information about detection and reduction of PQ problems. Substantial reduction of total harmonic distortion of current is observed with application of suitable wavelet tool than compared to passive filters [4].

II. MITIGATION METHODS

The different mitigation methods that are available for avoiding and resolving harmonics in induction furnaces are, use of balanced reactors, surge suppressors, voltage regulators, superconducting magnetic energy storage (SMES), increased line insulation, harmonic filters etc. The proposed methods to improve PQ include implementation of passive filter design for optimal solution and wavelet transform technique.

A. Passive Filters

Filters are used to pass signals or currents at certain frequencies to the intended load, while the unwanted frequencies are shunt to ground or sent back to their source. These filters often provide the least-cost solution for reduction of harmonics for the existing system. They are classified into two types, viz., active filters and passive filters. Active filters are commercially viable products that are used only for high-power applications, where power factor correction capacitors already exist. Hence, it is cost effective to use passive filtering.

Passive filters can be combination of either inductive impedance or a capacitive impedance to achieve filtering capabilities. They offer low impedance path for the flow of harmonic currents, which can be implemented for large sizes of MVArs. They do not consist of any amplifying elements like transistors, op-amps, etc. hence they do not possess signal gain. Thus, their output levels are always lesser than the input. The advantages of such passive filters when compared to digital filters are: they can handle large currents and high voltages, very reliable, least number of components for given filter, allows less power consumption, no bandwidth limitation, robust and relatively inexpensive, low maintenance, for power quality improvement with power factor correction and reactive power compensation and they also offer fast response time which is essential for non-linear load To achieve an acceptable distortion limits, different types of passive filters are accomplished. The most commonly used passive filters are low pass filters, high-pass filters, band-pass filters (single-tuned and double-tuned filter) and C-type high-pass filter [5] as shown in Fig.1.

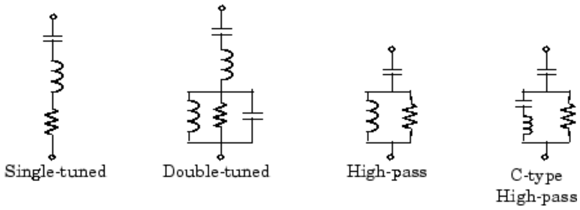


Fig. 1: Different types of passive filters

The measure of sharpness for tuning frequency is given by the Quality factor (Q), which is a dimension less parameter, defined as the ratio of stored energy with respect to the lost energy per unit time. The Q of the filter can also be expressed as the quality factor of the reactance at the tuning frequency, Q = (n. XL)/R. Single tuned LC filter are normally tuned for a specific frequency. Such filters are most widely used in electronics applications like amplifiers, oscillators, tuners, mixers, etc. They are most commonly used in star-delta combination. Double-tuned filters are a type of band-pass filters that are tuned at two frequencies. Their losses are much lesser and the impedance magnitude at the frequency of the parallel resonance that arises between the two tuning frequencies is also lower.

High pass filters are used for higher order harmonics with wide range of frequencies. They are the most commonly used filters that remove the noise signals at power lines. C-type high pass filter is one of special type of high pass filter. It provides reactive power compensation and avoids parallel resonance and also keeps zero losses at fundamental frequency.

B. Wavelet Transform

Wavelet Transform (WT) and its applications are rapidly developing fields in applied mathematics and signal analysis. The WT has been widely used for analyzing the PQ problems. The WT approach prepares a window that simultaneously gives proper resolutions in both the time and the frequency domain. Fourier transform decomposes the signal into sine and cosines, i.e. the functions localized in Fourier space. The wavelet transform uses functions that are localized in both the real and Fourier space [6]. Generally, the wavelet transform can be expressed by the (1).

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi\left|\frac{t-b}{a}\right| a,b \in R, a \neq 0 \qquad (1)$$

A particular version of wavelet is selected as the basis function commonly referred as the mother wavelet. The parameter ‘a’ is the scaling parameter. The parameter ‘b’ is the translation parameter which determines the time location of the wavelet. If $|a| < 1$, then the wavelet in is the compressed version (smaller support in time- domain) of the mother wavelet and corresponds mainly to higher frequencies. On the other hand, when $|a| > 1$, then $\psi_{a,b}(t)$ has a larger time-width than $\psi(t)$ and corresponds to lower frequencies. Thus, wavelets have time-widths adapted to their frequencies. The general representation of wavelet transform is given by (2), which is scalar product of mother wavelet $\psi(t)$ and signal f (t).

$$\left\langle f, \psi_{j,k} \right\rangle = d_{j,k} = \int_{-\infty}^{\infty} f(t)\psi_{j,k}(t)dt \qquad (2)$$

Multi-resolution analysis (MRA) is a mathematical method of modern signal processing that allows one to analyze the properties of signals of interest at different resolution levels and multi-resolution representation of an image gives us a complete idea about the extent of the details existing at different locations from which we can choose our requirements of desired details [7]. In wavelet analysis, the approximations (A) are the high scale- low frequency components of the signal and the details (D) are the low scale- high frequency components. The diagram shown in Fig.2 represents filtering process, where the original signal S, passes through two complementary filters and emerges as two signals.

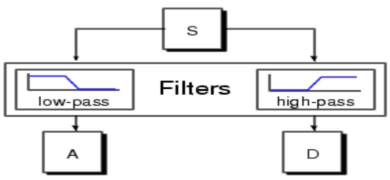


Fig. 2: Filtering with high and low pass filters

Multiple-Level Decomposition is the decomposition process that can be iterated with successive approximations being decomposed, such that one signal is fragmented into many lower-resolution components. This is referred to as the wavelet decomposition tree. The A and D coefficients can be used to reconstruct the signal perfectly when run through the mirror reconstruction filters of the wavelet family shown in Fig. 3.

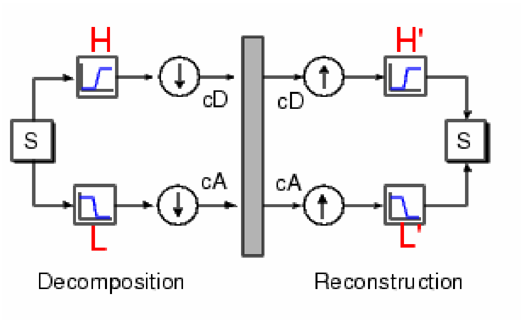


Fig. 3: Decomposition and Reconstruction of signal with approximation and detail coefficients

The percentage reduction in amplitude of a signal before and after applying wavelet transform technique is referred to as reduction in percentage amplitude (RPA) as expressed in (3).

$$RPA = \frac{\text{peak value of original signal} - \text{peak value of filtered signal}}{\text{peak value of original signal}} \times 100 \qquad (3)$$

III. HARMONIC ANALYSIS

Harmonics are AC voltages and currents with frequencies that are integer multiples of the fundamental frequency. Normally, only odd-order harmonics (3^{rd}, 5^{th}, 7^{th}, 9^{th}…) occur in three phase power system. The frequency of inter-harmonics are not integer multiples of the fundamental frequency. They appear as discrete frequencies or as a band spectrum. The main sources of harmonics are rectifiers, inverters, fluorescent lamps, TVs, laser printers, SMPS, computers, electronic ballast, refrigerators, induction furnaces, UPS and other nonlinear loads.

Major effects of harmonics include mal-operation of control devices, additional heating and losses in cables due to skin effects, dielectric breakdown, abnormal time delay in switching circuitry and false tripping that occur due to high frequency currents.

Induction furnace is one such nonlinear load, which draws high inrush current that is non-sinusoidal in nature. Thereby, it leads to generation of harmonics in the entire system. Due to this, overheating occurs and it leads to insulation breakdown, failure of fuses and other disturbances. These noise problems also generate additional vibrations with the respective harmonic frequency. Thus, the overall disturbances result in flow of wrong pulses in the data transmission systems [3].

The most common harmonic index used to indicate the harmonic content of a distorted waveform with a single number is the total harmonic distortion (THD). THD is expressed in percentage or in dB relative to the fundamental as distortion attenuation. It is defined as the ratio of the RMS amplitude of a set of higher harmonic frequencies to the RMS amplitude of the first harmonic or fundamental frequency. The voltage total harmonic distortion THD (V) and current total harmonic distortion THD (I) of individual orders of V_n and I_n respectively are expressed as given in (4) and (5).

$$THD(I) = \sqrt{\frac{I_2^{\,2} + I_3^{\,2} + \ldots\ldots + I_n^{\,2}}{I_1}} \times 100 \qquad (4)$$

$$THD(V) = \sqrt{\frac{V_2^{\,2} + V_3^{\,2} + \ldots\ldots + V_n^{\,2}}{V_1}} \times 100 \qquad (5)$$

General methods for reduction of harmonics include high power quality equipment design, optimal placement and sizing of capacitor banks, harmonic cancellation, de-rating of power system devices, passive, active and hybrid filters, custom power devices such as active power line conditioners, unified or universal power quality conditioners, phase shifting transformers, implementation of wavelet transform technique, genetic algorithm and artificial neural networks, etc.

IV. SIMULINK MODEL OF INDUCTION FURNACE

Figure 4 represents the block diagram of a furnace with inductive load where the three phase ac input supply is given through an AC to DC converter. The ac voltage is converted into dc voltage; the output so obtained is fed to the DC to AC inverter which leads to production of high frequency ac voltage and current. These high frequency ac components are fed to the induction furnace coil, which works on the principle of electromagnetic induction.

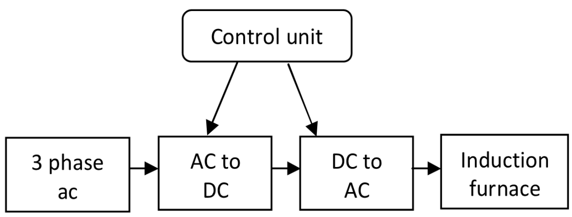


Fig.4: Block diagram of furnace with inductive load

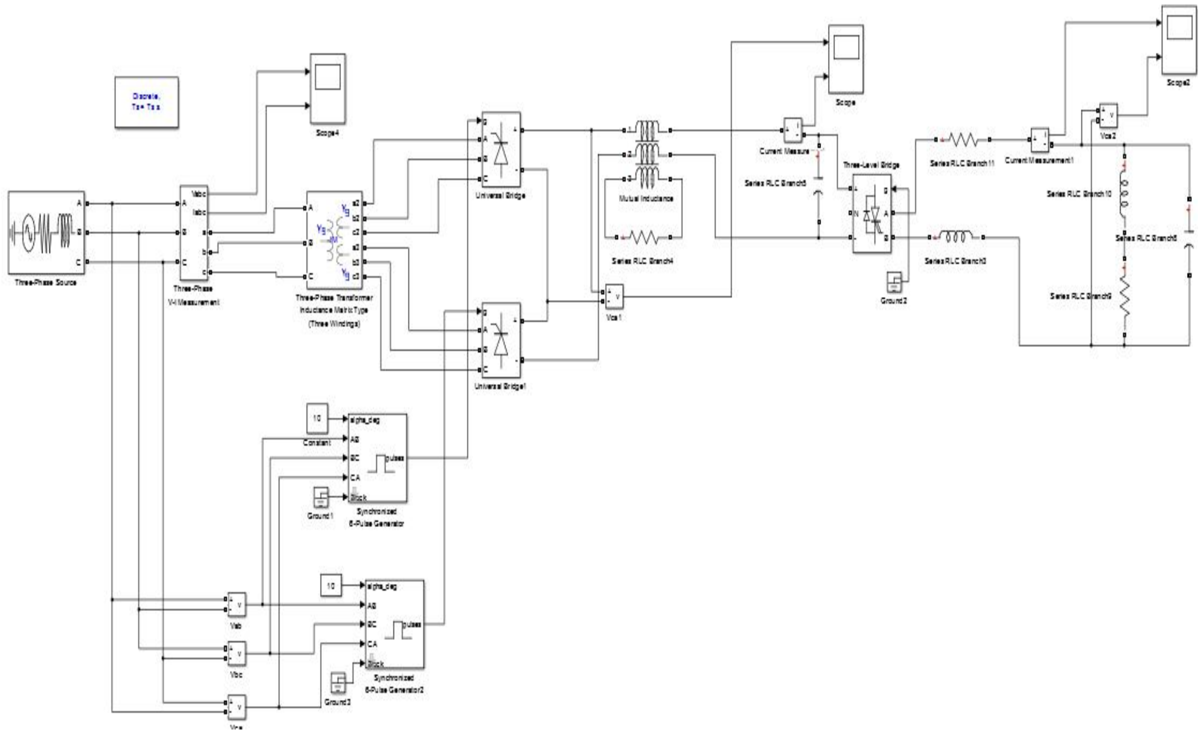


Fig. 5: Simulink model of Induction Furnace

In order to approach with better overview and operational behaviors of induction furnace, a Simulink model is developed in MATLAB [8]. By means of simulation methods, the harmonic study and electrical performance of the induction furnaces will be acknowledged.

Figure 5 represents the Simulink model of induction furnace. An approximate model is designed based on the schematic diagram of the induction furnace at the installation, which depends on the power range and transformer ratings of the furnace [8]. The three phase supply is given to primary side of tertiary winding transformer, two three phase rectifiers connected to the secondary side of the transformer convert AC voltage to DC voltage such that the current flows unidirectional. The output obtained from these rectifiers is connected in series to obtain higher level of DC voltage. The pulses are generated using six pulse generator for each bridge. After rectification, the DC voltage is given either as voltage fed or current fed inverter. This results in producing higher level of AC voltage and current. Thus, a high frequency AC supply is given to an induction furnace load. Induction coil is considered as a combination of basic components such as resistor, inductor and capacitor with suitable ratings and based on the type of induction furnace [8].

V.PROPOSED ALGORITHM

The harmonic analysis of induction furnace was carried out based on wavelet algorithm as shown in Fig.6. The distorted signal to be analyzed was taken from PQA and fed to the wavelet filters. The signal was decomposed using MRA for different scales and positions depending upon the type of wavelet filters db1 to db45. Appropriate filters were selected based on THD and RPA of the filtered signal.

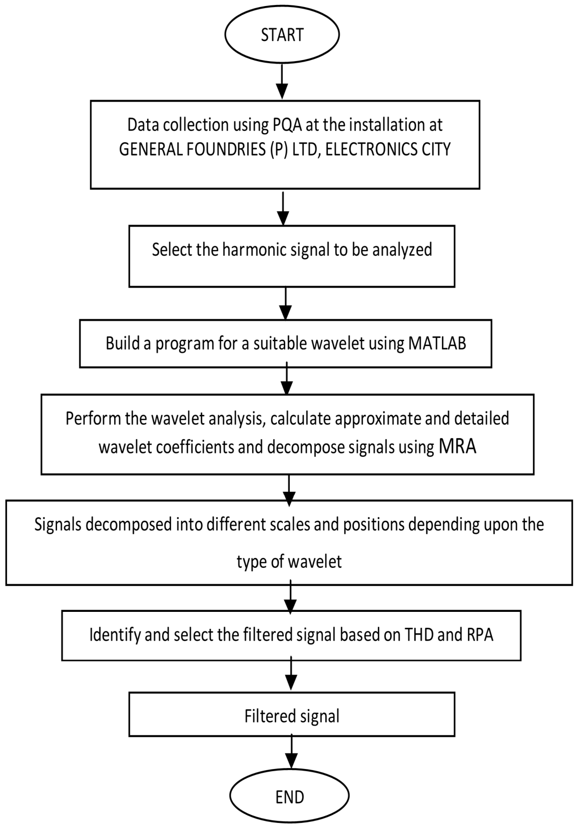


Fig. 6: Flowchart of proposed algorithm

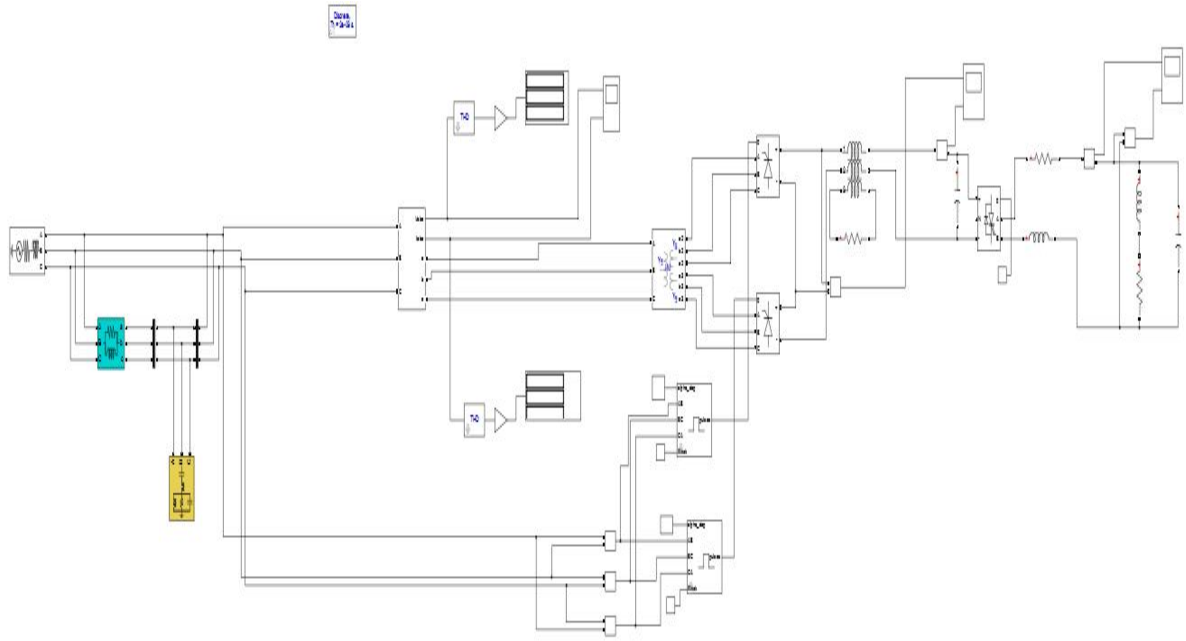


Fig. 7: Simulink model of induction furnace with filter

VI. RESULTS AND DISCUSSIONS

A.Passive filter implementation

The Simulink model of induction furnace shown in Fig. 5 is executed in MATLAB with passive filters as shown in Fig.7. The current waveform obtained with distortion is as shown in Fig. 8, where the current THD at supply side was obtained as 15.01% same value as tabulated from PQA.

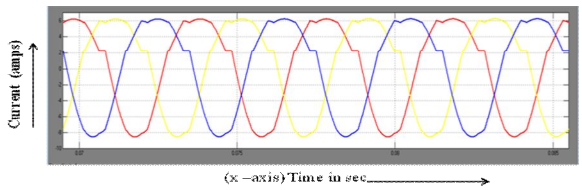
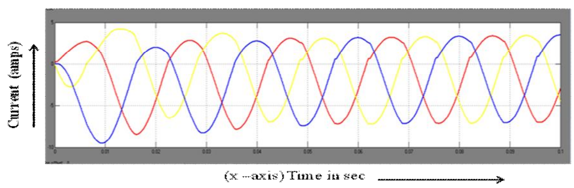


Fig. 8: Current waveform at supply side (without filter)

A typical Low pass filter was inserted at the supply end as shown in Fig.7, with L=10mH and C=125mF. Fig. 8 represents current waveform at supply side with reduced harmonic distortions after simulation. The current THD was reduced from 15.01% to 11.47%.

With reference to the Simulink model shown in Fig.7, the other types of filters like double tuned, high pass and C-type high pass filter were implemented and the filtered current waveform obtained after simulation are as shown in Fig. 9.



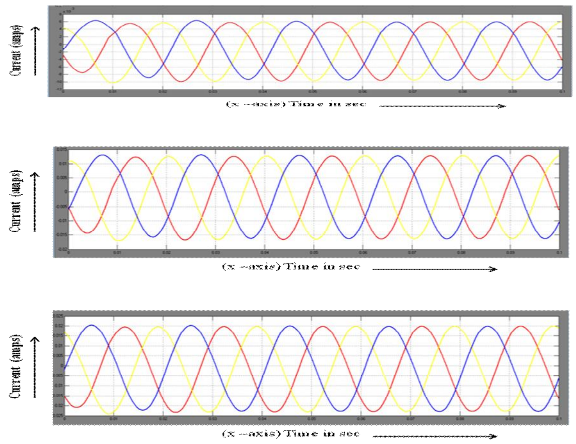


Fig. 9: Current waveform at supply side with (a) LC, (b) Double tuned, (c) High pass and (d) C-Type high pass filters

The harmonic analysis carried out for LC, double tuned, high pass and C-Type high pass filters is as tabulated in Table. 1. It gives an overview of all simulations carried out with different types of passive filters in the Simulink model of induction furnace.

Table.1: Comparison of THD for different types of passive filters

Type Of Filter	Parameters	Current THD (%) (For All 3 Phases R-Y-B)
Without Filter	--	15.01 14.95 15.04
LC	L=10mH C=125mF	11.47 11.77 11.33

Double Tuned	R=55 Ω L=150mH	5.65 5.65 5.51
High Pass	R=30 Ω L=50mH	3.02 3.02 2.92
C Type High Pass	R=10 Ω L=45mH	2.06 2.06 1.98

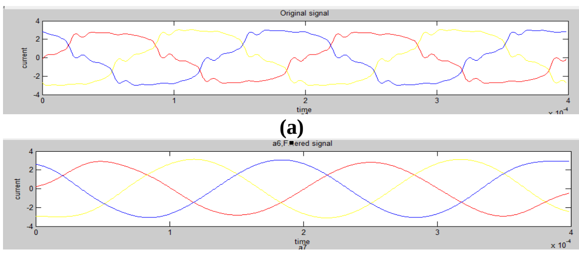
Observation:
The THD of current for C-Type high pass filter is 2.06% which is found to be the least among all the filters implemented with a net reduction of 86.65% compared to the original signal.

B. Implementation of Wavelet Transform:
Data collection at the installation of induction furnace shown in Table2, as obtained from PQA connected at supply side at the installation of induction furnace. Current distortion was observed to be 15.23%.

Table 2: Power supply data at supply end - as observed from PQA.

3 Phase supply	V volts	I Amps	Real power	Reactive power	Apparent power	Power factor	V_{thd}	I_{thd}
R	403.74	316.67	-0.4557k	-0.0797k	0.4626k	-0.9851	4.99%	15.23%
Y	405.55	322.48	-0.4634k	-0.0799k	0.4703k	-0.9855	5.09%	15.08%
B	406.26	315.33	-0.4558k	-0.0797k	0.4627k	-0.9851	4.96%	15.39%

Data obtained from PQA is further analyzed using WT. Daubechies wavelet is one of the most widely used wavelet. It gives exact decomposition and reconstruction of the signal at a faster rate and flexible algorithm with sufficient number of vanishing moments. Harmonic analysis was carried out based on wavelet algorithm as shown in Fig. 6, for the wavelet orders from db1 to db45 [9] & [10]. The current waveforms were observed for 10 levels (a_1 to a_{10}) where the original signal was found to be successfully filtered at 6th level (a_6), as it provides better reduction of THD. Original and filtered signals for db11 are as shown in Fig. 10. The filters db7, db11, db12 and db15 exhibited better performance than their counter parts like db2, as tabulated in Table 3.



(a)

(b)

Fig. 10: Analysis using Daubechies (db11) wavelet: (a) Original signal, (b) Filtered signal @6th level

Table 3: Comparison of THD for different Daubechies

Type of wavelet	THD (%)	5th harmonic order (%)	RPA (%)
Original signal	15.23	10.75	---
db2	11.415081	7.81	-14.078
db7	0.602945	0.25	-2.446
db11	0.385557	0.13	-0.7092
db12	0.617370	0.12	2.269
db15	0.517693	0.19	0.2482

Observations:
Wavelet transform technique was implemented for filters db1 to db45. The lowest THD was recorded for db11, where THD of current at supply end is reduced from 15.23% to 0.385557 % with net reduction of 97.47% and the peak amplitude of filtered signal displayed percentage reduction in peak amplitude of 0.7092%. The 5th harmonic order that was found to be predominant at 10.75% was reduced to 0.13%, with net reduction of 98.76%

CONCLUSION

This paper presented PQ problems due to non-linear load like induction furnace and discussed the techniques to mitigate harmonics for power quality improvement. The Simulation based passive filter was designed for lower order harmonics viz. 3rd, 5th and 7th. Harmonic analysis was carried out using Wavelet Transform technique and it gives effective analysis at different resolution levels. Implementation of wavelet transform technique is more advanced and effective than the passive filtering method, since the total harmonic distortion of the original signal is greatly reduced in wavelet analysis than compared to that of the passive filters. Further research is being carried out to select the order of wavelet filters based on the performance of parameters like signal to noise ratio, mean square error and wavelet energy coefficient of signals.

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