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# Harmonic Analysis Using Artificial Neural Network

SabeehaBademiya[1],Manjula S Sureban[2]

1 P.G. Scholar, Department of Electrical and Electronics Engineering, SDMCET, Dharwad, India
2 Asst.Professor, Department of Electrical and Electronics Engineering, SDMCET, Dharwad, India

**Abstract**—The increasing application of power electronic facilities in the industrial environment has led to serious concerns about source line pollution and the resulting impacts on system equipment and power distribution systems. Consequently, passive or active power filters have been used as an effective way to compensate harmonic components in nonlinear loads. Obviously, fast and precise harmonic detection is one of the key factors to design power filters. Various digital signal analysis techniques are being used for the measurement and estimation of power system harmonics. Presently, neural network has received special attention from the researchers because of its simplicity, learning and generalization ability. This paper presents a neural network based algorithm that can estimate the total harmonic distortion present in the output form power electronic converter. Comparison with the Fourier series method is presented to demonstrate the fast response and high accuracy of neural networks.

**Index Terms**—Harmonics, Fourier series, Fourier Transform, Power filters, Artificial neural network



## 1 INTRODUCTION:

Harmonics are mathematical way of describing distortion to a voltage or current waveform. The term harmonic refers to a waveform that occurs at an integer multiple of the fundamental frequency. Fourier theory tells us thatany repetitive waveform can be defined in terms of summing sinusoidal waveforms which are integer multiples (or harmonics) of the fundamental frequency. For the purpose of a steady state waveform with equal positive and negative half-cycles, the fourier seriescan be expressed as follows:

$$f(t) = \sum_{n=1}^{\infty} An \sin(n\Pi t/T)$$

Where
**f(t)** is the time domain function
**n** is the harmonic number (only odd values of n are required)
**$A_n$** is the amplitude of the nth harmonic component
**T** is the length of one cycle in seconds

A common term that is used in relation to harmonics is THD or Total Harmonic Distortion. THD can be used to describe voltage or current distortion and is calculated as follows:

$$THD(\%) = \sqrt{(ID_1 2 + ID_2 2 + ......ID_n 2)}$$

Where
IDn is the magnitude of the nth harmonics as a pecentage of the fundamental (individual distortion).
Another closely related term is distortion factor(DF) Which is essentially the same as THD.

## 2 CAUSES OF HARMONICS:

Harmonics are caused by non-linear loads that is loads that draw a non-sinusoidal current from a sinusoidal voltage source. Some examples of harmonics producing loads are electric arc furnaces, static VAR compensators, switch-mode power supplies, and AC or DC motor drives. In the case of a motor drive, the AC current at the input to the rectifier looks more like a square wave than a sinewave (see Figure 1).

Fig. 1 Typical 6-pulse rectifier input current waveform

The rectifier can be thought of as a harmonic current source and produces roughly the same amount of harmonic current over a wide range of power system impedances. The characteristic current harmonics that are produced by a rectifier are determined by the pulse number. The following equation allows determination of the characteristic harmonics for a given pulse number:

h = kq±1
where
**h** is the harmonic number (integer multiple of the fun

damental)
**k** is any positive integer
**q**is the pulse number of the converter

This means that a 6-pulse (or 3-phase) rectifier will exhibit harmonics at the 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, etc. multiples of the fundamental. As a rough rule of thumb, the magnitudes of the harmonic currents will be the fundamental current devided by the harmonic number (e.g. the magnitude of the 5th harmonic would be about 1/5th of the fundamental current). A 12-pulse (or 6-phase rectifier) will, in theory produce harmonic currents at the 11th, 13th, 23rd, 25th, etc. multiples. In reality, a small amount of the 5th, 7th, 17th and 19th harmonics will be present with a12-pulse system.

Variable frequency drives also produce harmonic currents at the output of the inverter which are seen by the motor. Most of these harmonics are integer multiples of the inverter operating frequency and not the power supply frequency, but the little generalization can be made about their magnitude since this varies greatly with the type of drive and the switching algorithm for the inverter semiconductors. some "interharmonic" currents may also be present at the input or the output of the drive. Interharmonics do not fit the classical definition of harmonics since they do not necessarily occur at integer multiples of power supply or inverter fundamental frequency. Harmonics can occur on the input at the power system frequency plus or minus the inverter operating frequency. The inverter output can contain harmonics at the rectifier pulse number times the power system frequency plus or minus the inverter operating frequency. Proper DC link design can minimize the presence of interharmonics.

## 3 METHODS OF HARMONIC ANALYSIS:

Harmonic analysis is a branch of mathematics concerned with the representation of functions or signals as the superposition of basic waves, and the study of generalization of the notions of fourier series and fourier transforms.

The summary below shows the phase sequences of odd harmonics

- Harmonics of order h = 1, 7, 13, are all positive sequence.
- Harmonics of order h = 5, 11, 17 are all negative sequence.
- Triplens (those who are multiples of 3) h = 3, 9, 15 are called zerosequence

**Odd harmonics:**

Fig. 2 shows the graph of an odd harmonic Fourier series. The Fourier series will contain odd harmonics if

$f(t + \pi) = -f(t)$

In this case, the fourier expansion will be in the form of;

$f(t) = \frac{a0}{2} + (a1cost + b1sint) + (a3cos3t + b3sin3t) + \ldots\ldots$ all of the harmonics are odd

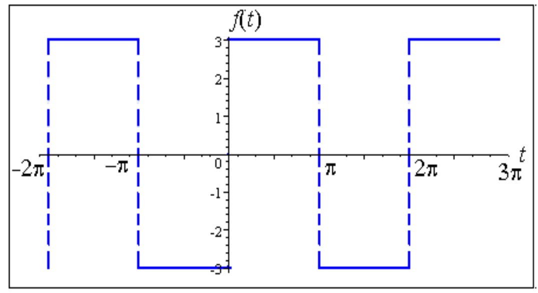


Fig. 2: Odd harmonics.

**Even harmonics:**

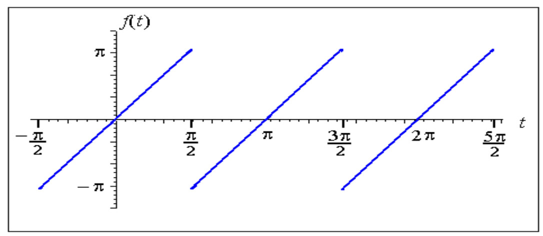


Fig.3: Even harmonics.

The Fourier series as shown in Figure 3 will contain even harmonics
if
$f(t + \pi) = f(t)$

In this case, the Fourier expansion will be of the form:

$$f(t) = \frac{a0}{2} + (a2\cos 2t + b2\sin 2t) + (a4\cos 4t + b4\sin 4t) + \ldots..$$

**Fourier transform:**

The Fourier transform is an extension of the Fourier series that resultswhen the period of the represented function is lengtened and allowedto approach infinity. Basically Fourier Transform is a mathematicaloperation used to decompose a signal into sine and cosine components Fig. 4.
Fundamentally Fourier Transform is a mathematical operation used to break a signal into sine and cosine components. The result of the alteration represents the signal as a function of frequency while theinput signals as a function of time. It can refer into 4 categories.

- Aperiodic-Continuous (Fourier transform)
- Periodic-continuous (Fourier Series)
- Aperiodic-Discrete (Discrete-time Fourier Transform)
- Periodic-Discrete (Discrete Fourier Transform)

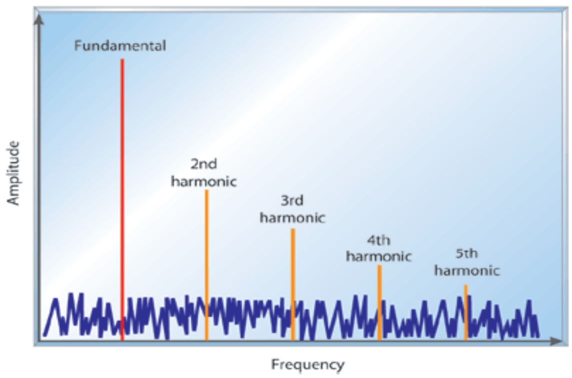


Figure 4: Fourier transform of harmonics

## 4 THREE PHASE HARMONIC FILTER:

A three phase harmonic filter is a connection of parallel elements that are useful in a power system in order to decrease the voltage distortion and to correct the power factor. Harmonic elements such as electronic converters produce harmonic currents and harmonic voltages or both at the same time. These distortions are injected into the power system. This will in turn produce a distorted current flow through the impedanceof the system which will yield to the produc-tion of harmonic voltage distortion. Harmonic filters wheth-er single phase or three phase are used to reduce this distor-tion by guiding the harmonic currents to the path where there is a relatively low impedance. Harmonic filters are ca-pacitive at the base or fundamental frequency and they can also be used for producing reactive power which will be re-quired by the converters for purpose of power factor correc-tion. In order to achieve an acceptable distortion limit, a lot filter banks are usually connected in parallel, the most commonly used of these filters are;

- Band pass filters: these filters are used to filter low order ha monics like the 5th, 7th, 11th, 13th etc. these filters can be in two forms namely; single tuned and double tuned single tuned filter is operated at one frequency while the double tuned filter is o erated at two frequencies.

- High pass filters: These filters are used to filters high harmonic frequencies as the name implies. A special type of high pass filter called the C type filter was used in this thesis to provide reactive power and to stop parallel resonance. It enables the filtering of lowest order harmonic that is the 3rd ha monic as well as keeping zero losses at the base frequency.

- Three phase harmonic filters: This filter is built with RLC elements. These RLC values are determined from the form of the filter using the following parameters.

- Reactive power at the nominal voltage
- Tuning frequency
- Quality factor.

The four types of filters that can be designed along side the three phase harmonic filter are shown below.

The simplest form of these filters is the single tuned, that is the one that is operated using only one frequencyand Figure 5 shows the quality factor and formulae for calculating the reative and active powers respectively. The quality factor Q of the filter is given as, $\mathbf{Q = nX_L/R}$
The quality factor Q indicates the bandwidth B which measures the sharpness of the tuning frequency.

Fig 5: Different types of three-phase RLC harmonic filter.

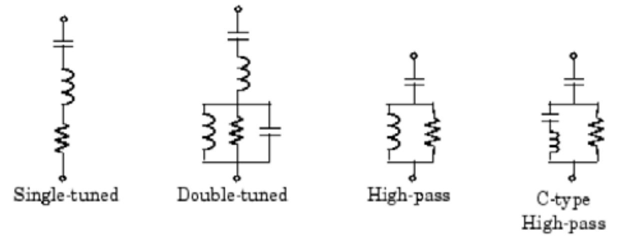


Fig. 6: three phase harmonic filter (Simulink diagram)

## 5 CASE STUDY:

The HVDC line in the system's rectifier was gotten from the two 6 pulse thyristor bridges that were connected in series. Connected to the system is also a converter with a 120MVA three phase transformer. Connected to the DC side is a 1000MW resistive load through a 0.5H smoothening reactor Figure 6. The filters comprise of the following four components of the power lib library.

- One capacitor bank C1 of 150Mvar designed by a "Three Phase Series RLC Load",
- Three filters designed using the "Three-Phase Harmonics Filters" are used in the HVDC line as shown in the Figure 6.
- One C type filter tuned to the 3rd F1 of 150Mvar.
- One double tuned filter 11th/13th F2 of 150Mvar.
- One high-pass filter tuned to the 24th (F3) of 150Mvar.

The filter is opened and closed with the breaker in the circuit. When the breaker is closed, the current and voltage from B1 will pass through the filter and will subsequently be filtered and can be seen through the scope. However, when the breaker is opened, the filter will be deactivated and will have no effect on the output waveforms of the system.

The following waveforms will show the filter effects on the output waveforms of the system Fig. 7.

With the breaker opened and the filter deactivated, a highly distorted waveform was formed as the result of the nonlinear loads in the system. Checking the FFT analysis of the system, we will also see a very high amount of THD which will be way above the accepted IEE- 519-1992 limits Fig. 8.

The FFT analysis of the voltage waveform at B1 above shows a highly distorted waveform and an unacceptable level of THDat 17.78%Figure 8.

The FFT also shows a highly distorted current waveform at B1 and an unacceptable level of THD at 12.59% Figure9. Now, by closing thebreaker, the filter will be activated, and the wavforms will be as follows;

The output from VI measurement B1 was connected to the filter,and hence, we can see the voltage and current at B1 were duly filtered toan almost ideal sinewave. The FFT analysis also showed that the THDwas significantly reduced to an accepted level Figure 10.

The FFT of the voltage ab B1 shows an almost ideal waveform and the THD was significantly reduced from 17.78% to 0.88% which is within the acceptable limits of the IEE-519-1992 Figure 11.

The FFT analysis of the current waveform at B1 also shows that the THD of the current waveform was reduced from 12.59% to 0.70% which is within the acceptable limits of THD Figure 12.

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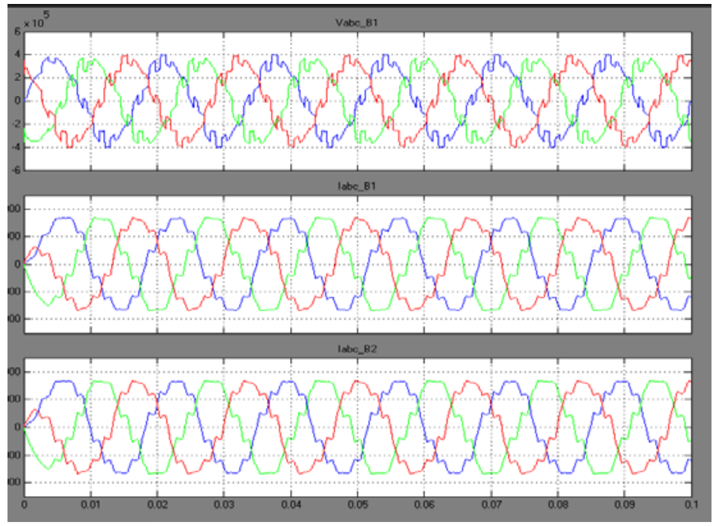



Fig. 7: Output Waveforms of the System with Filter Disconnected

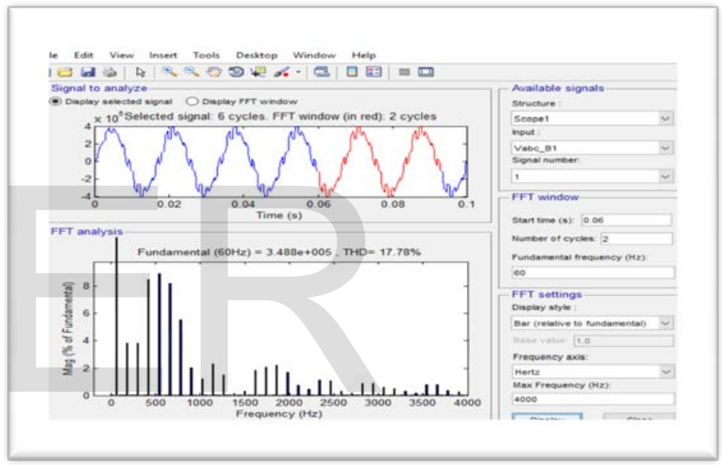



Fig. 8: FFT analysis of the voltage with filter disconnected.

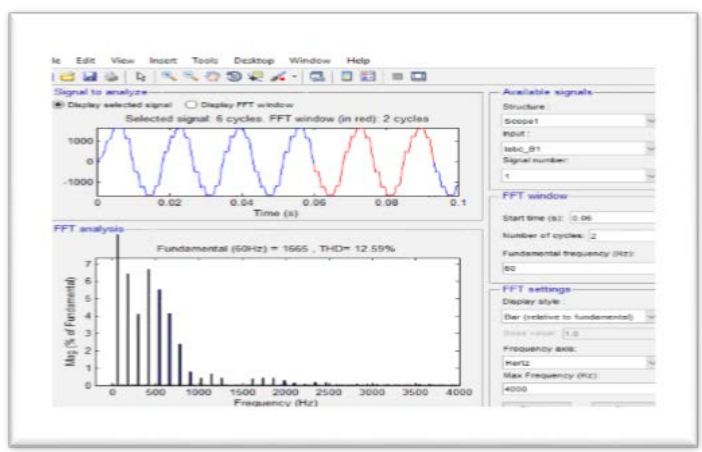



Fig. 9: FFT analysis of the current with filter disconnected.

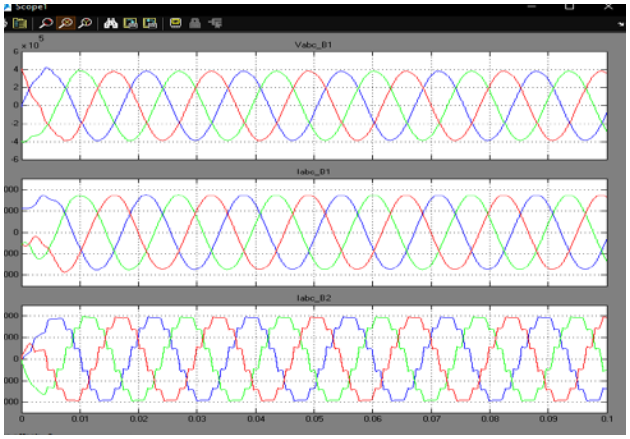


Fig 10: Output waveforms of the system with filter connected at bus B1.

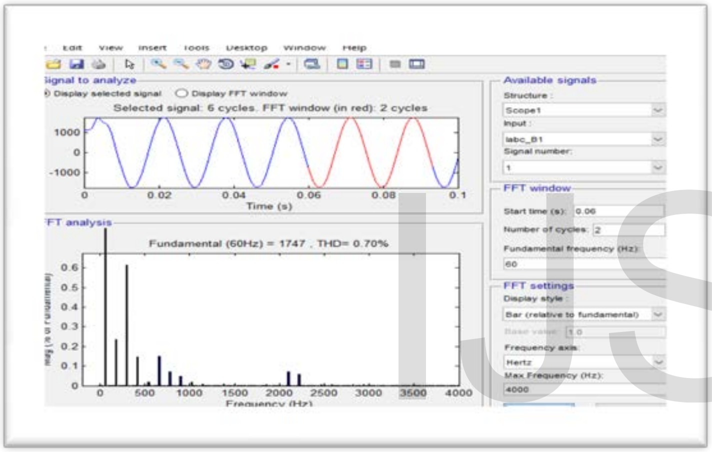



Fig. 11: FFT analysis of the voltage with filter connected

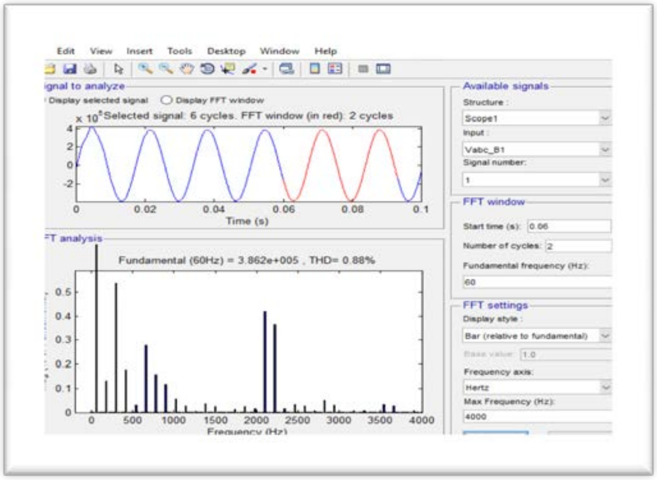



Fig12: FFT analysis of the current with filter connected

## 6 ANALYSIS USING ARTIFICIAL NEURAL NETWORK

Recently, there has been considerable interest in the application of Artificial Neural Network (ANN) to power system. ANN has the ability to classify complex relationships properly. The relationships classified by ANN are highly nonlinear and often result from large mathematical models. Once trained, the ANN can classify new data much faster than it would be possible by solving the model analytically: An integrated based system, ANN, and conventional power system solution methodologies have potential to provide real-time optimization and control of power system. This paper presents the application of ANN for harmonic analysis of power system.

### Data Set Preparation :

### Inputs:

The firing angle to rectifier is veried form 0 to 90 degree insteps of 3 which isconsidred as input set for training ANN. The corresponding THD and output DC voltage and current are considred as targets.

| nput 31 samples |
|---|
| 0 |
| 3 |
| 6 |
| 9 |
| 12 |
| 15 |
| 18 |
| 21 |
| 24 |
| 27 |
| 30 |
| 33 |
| 36 |
| 39 |
| 42 |
| 45 |
| 48 |
| 51 |
| 54 |
| 57 |
| 60 |
| 63 |
| 66 |
| 69 |
| 72 |
| 75 |
| 78 |
| 81 |
| 84 |
| 87 |
| 90 |

Table 1: input α in degrees

**Targets:**

| THD(%) | Vdc(kv) | Idc(KA) |
|---|---|---|
| 0.4 | 541.06 | 2.16 |
| 0.42 | 538.55 | 2.15 |
| 0.38 | 534.37 | 2.14 |
| 0.38 | 528.67 | 2.11 |
| 0.52 | 519.91 | 2.08 |
| 1.95 | 512.45 | 2.05 |
| 2.33 | 503.07 | 2.01 |
| 0.7 | 493.6 | 1.97 |
| 0.86 | 478.97 | 1.92 |
| 0.58 | 468.12 | 1.87 |
| 0.5 | 454.87 | 1.82 |
| 0.55 | 441.39 | 1.77 |
| 0.57 | 424.32 | 1.7 |
| 0.72 | 408.66 | 1.63 |
| 0.83 | 390.37 | 1.56 |
| 1 | 370.33 | 1.48 |
| 1.07 | 354.46 | 1.42 |
| 1.14 | 333.16 | 1.33 |
| 1.26 | 311.06 | 1.24 |
| 1.46 | 291.84 | 1.17 |
| 1.18 | 271.29 | 1.09 |
| 1.15 | 249.58 | 1 |
| 1.1 | 225.18 | 0.9 |
| 1.01 | 195.64 | 0.78 |
| 0.95 | 172.53 | 0.69 |
| 0.84 | 146.68 | 0.59 |
| 0.74 | 118.14 | 0.47 |
| 0.58 | 81.97 | 0.33 |
| 0.48 | 55.21 | 0.22 |
| 0.35 | 24.77 | 0.1 |
| 0.28 | 12.53 | 0.05 |

Table 2: Target system conditions

**Training ANN**:

In the welcome window of ANN toolbox fitting tool app is selected as shown in the figure 13.

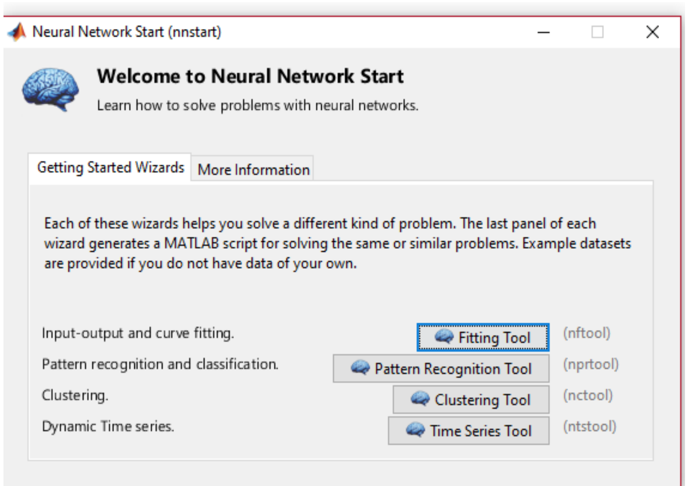



Fig. 13: Neural Network Start

The input and target sets are prepared by considering 30 values of firing angles, corresponding firing angles are considered as inputs and THD, output voltage and current are condiredas outputs and data sets are loaded first to excel sheet and then they are imported to MATLAB for training an ANN.

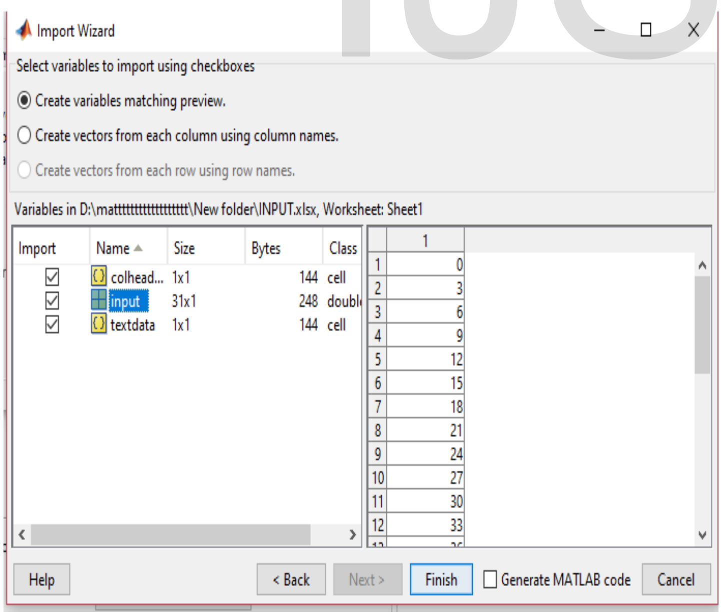
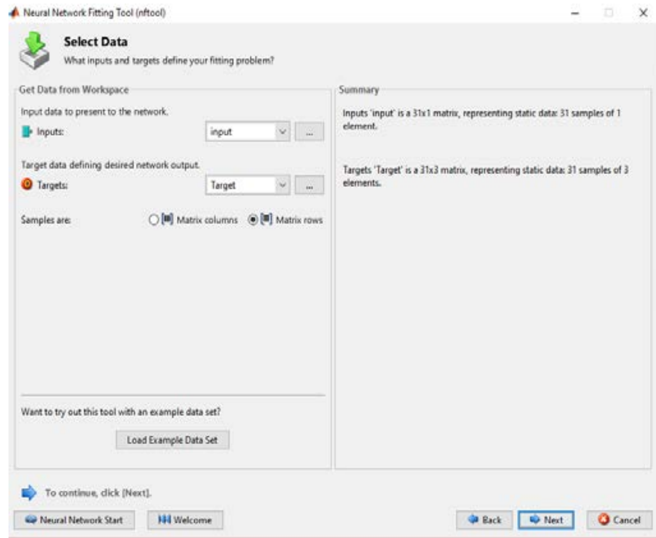



Fig. 14: Importing the INPUT and TARGET variables




Fig(15): Selecting inputs and targets for fitting tool Problem.

After importing the data ANN is trained using Levenberg-Macquardit algorithm. The correctness of the trained network is ensured by using Mean square error and regression value. The regression value near one shows that ANN is trained correctly and hence it can be used to produce the results for new set of data.



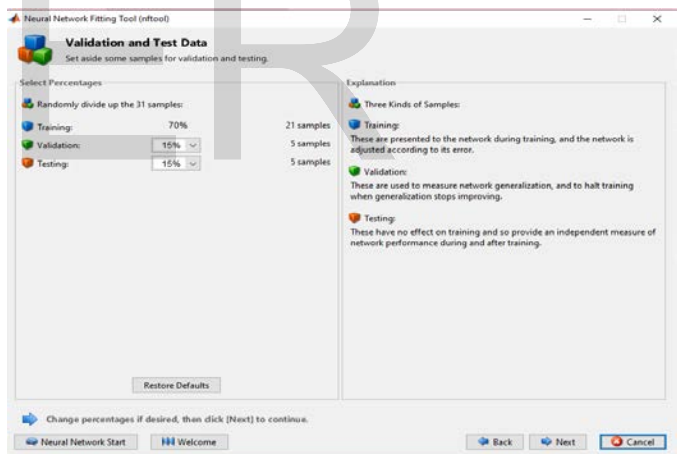



Fig. 16: Validation and Test Data

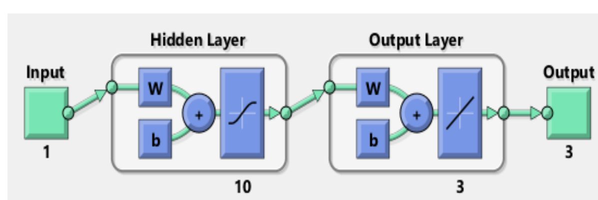



Fig. 17: Trained Neural Network

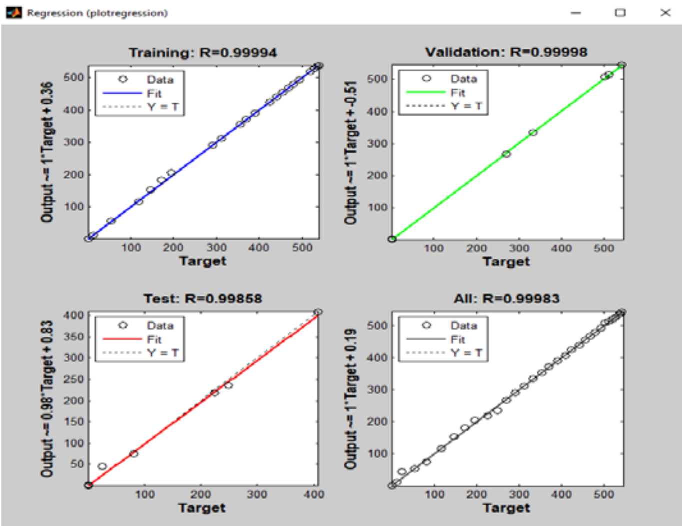



Fig. 18: Regression Plot

## 9 CONCLUSION:

The design of the three phase harmonic filter and its simultions was done using MATLABsimulink. Additionally, varieties of three phase filters were briefly discussed. These filters are also used in the HVDC line connected in parallel, all in the hope of achieving an acceptable distortion level. The HVDC line is used with a three phase filter to reduce harmonic distotion as well improving the overall quality of the power system. The results obtained from Simulink are used to train ANN using neural network toolbox of MATLAB and paerformance of the trained network is compared with those obtained form Simulink. From the results obtained in this paper, we can draw a conclsion that the filter is an effective method of mitigating harmonics at different frequencies and ANN is better approach for estimating harmonic distortion.



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