B. TECH. PROJECT REPORT

On

Harmonics Amplitude Estimation in Distribution Systems under Noisy Conditions

BY

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DISCIPLINE OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Harmonics Amplitude Estimation in Distribution Systems under Noisy Conditions

A PROJECT REPORT

Submitted in partial fulfillment of the

requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

Submitted by:

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Guided by:

Dr. Amod C Umarikar

INDIAN INSTITUTE OF TECHNOLOGY INDORE

December 2018

CANDIDATE’S DECLARATION

We hereby declare that the project entitled **Harmonics Amplitude Estimation in Distribution Systems under Noisy Conditions** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in **ELECTRICAL ENGINEERING** completed under the supervision of **Dr. Amod C Umarikar, Associate Professor, Electrical Engineering Department,** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of my knowledge.

Signature of BTP Guide(s) with dates and their designation

<u>Preface</u>

This report on **Harmonics Amplitude Estimation in Distribution System under Noisy Conditions** is prepared under the guidance of **Dr. Amod C Umarikar**.

With great increase in use of power electronic devices, it is need of the hour that a fast and efficient way to estimate and monitor harmonics is developed and implemented in real time. It would help mitigate the losses in power systems and constant monitoring would enable protection of power grid and electronic devices connected to it.

Bhavesh Mahawar

Aditya Deo

B.Tech. IV Year

Discipline of Electrical Engineering

IIT Indore

Acknowledgements

We wish to thank Dr.Amod C Umarikar for his kind support and valuable guidance.

It is their help and support, due to which we became able to complete the design and technical report.

Without their support this report would not have been possible.

Bhavesh Mahawar

Aditya Deo

B.Tech. IV Year

Discipline of Electrical Engineering

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Abstract

Harmonics, due to rise in use of electronic power devices, have become a significant factor which contributes to the loss of power. They also pose a threat to smooth functioning of Power Grids. They can not only disrupt the flow but also cause economic losses and damage the sensitive electrical equipments. Thus, it is important to have a fast, accurate and reliable method to determine the amplitude of various harmonics present in a power signal. This report presents one such method which works and has been implemented in real time to provide results. A TMS320F2839D Digital Signal Controller has been used to successfully implement this with the help of Code Composer Studio v8.1.0.

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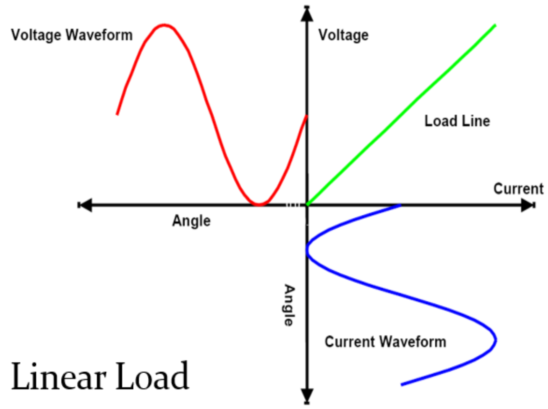
Introduction

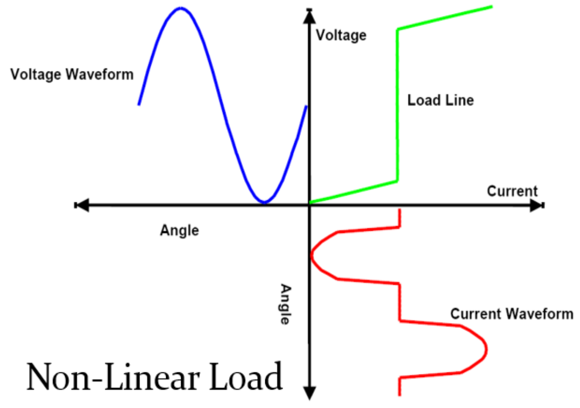
Electric devices and Power Transmission Systems have evolved with growing need and dependence of modern industry and society. Harmonics which have always existed in power systems did not create lot of problems in older days when the instruments used were less sophisticated however, due to great increase in use of electronic devices in industries as well as the electronic age household, harmonics present in power system have increased many times. Thus, dealing with problems which arise due to presence of harmonics in power systems are now of utmost significance. A modern power transmission system, thus, needs a system which can be fast and can accurately monitor harmonics present in the power system, so as to enable maximum efficiency in power transfer and usage. Such a system will help in online monitoring of harmonics and would help identify the sources of harmonics and assist in designing of active power filters used to mitigate the harmonics, and metering of harmonics.

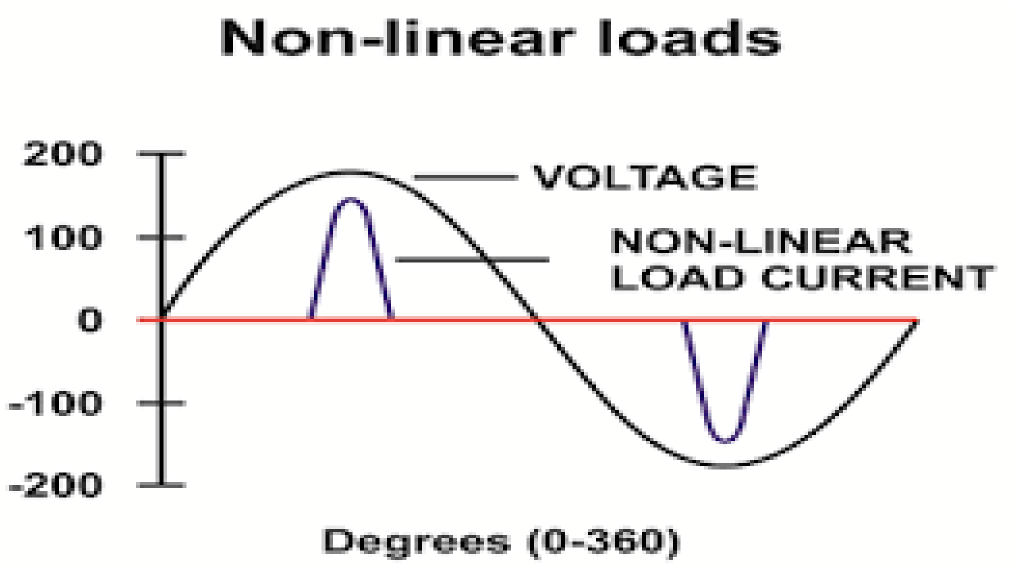
Types of Loads

Non-Linear Load devices, devices in which the current flow is not proportional to the voltage, are primary sources of harmonics. In earlier power systems, Linear Load devices, devices in which the current flow is proportional to voltage, were prevalently used, thus presence of harmonics was negligible. In linear loads, the impedance of the device remains constant despite variation in voltage, thus current drawn by the device for an input sinusoidal wave is a sinusoid. Incandescent lamps, heaters, motors and transformers are examples of linear loads between their work ratings.

In non-linear loads like DC/AC convertors, switch controllers, microprocessor based devices and arc furnaces, the impedance of the device varies with the applied voltage, hence the current through such a device when a sinusoidal voltage is applied to it, though periodic is not of sinusoidal nature. This distortion in current contributes power wastage which greatly increases the power loss compared to that of loss due Linear Load devices.

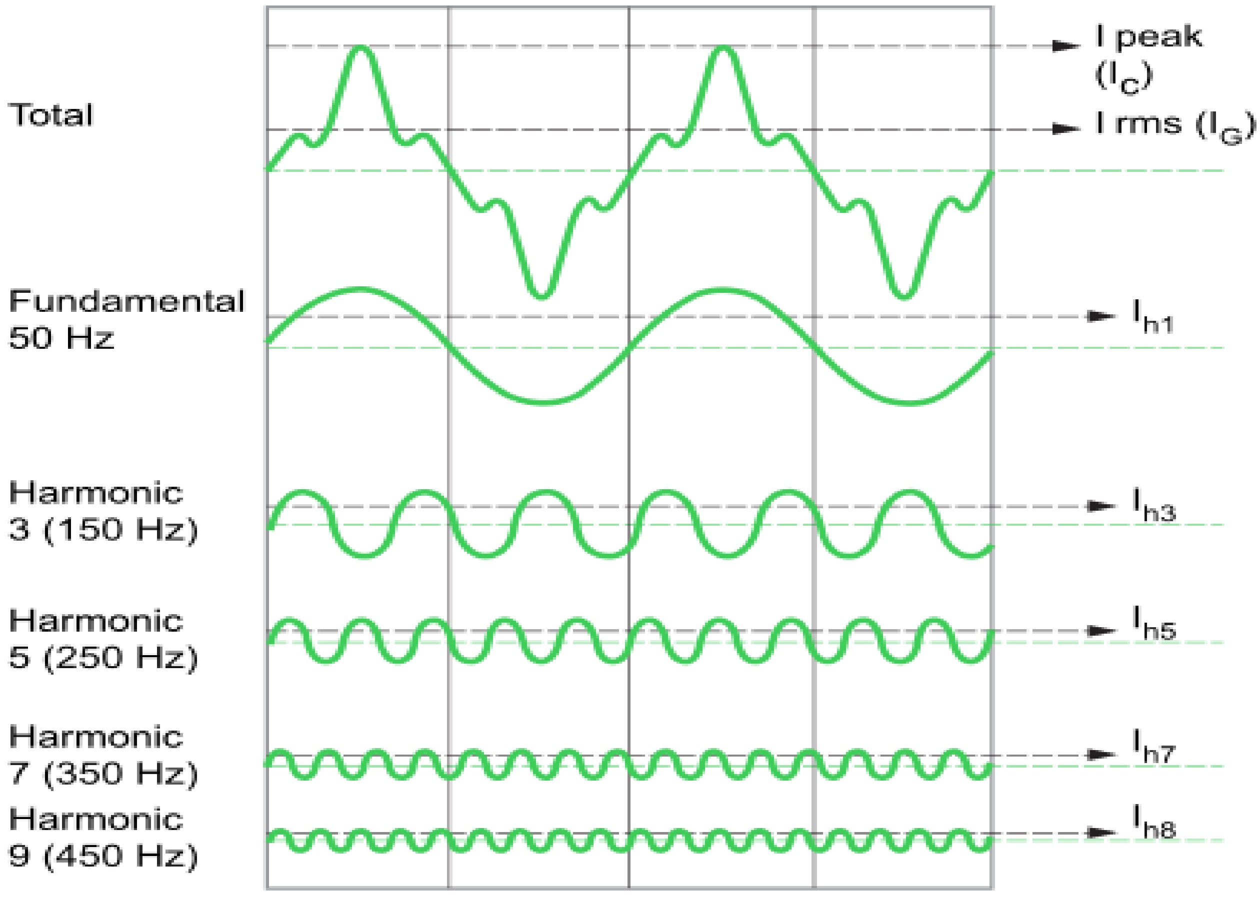






What are harmonics?

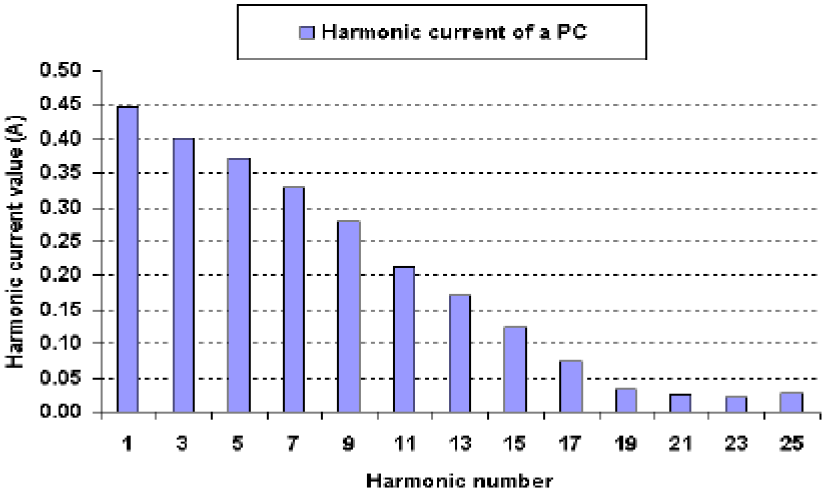
Harmonics are currents or voltages with frequencies that are integer multiples of fundamental frequency (50Hz in India) for example, 3rd harmonic would have frequency of 150Hz and 5th Harmonic would have frequency Individual harmonics frequency will vary in phase as well as amplitude depending upon the source which generates it. These additional frequencies distort the original signal waveform and lead to undesirable impacts. We mainly focus only on the odd harmonics as even harmonics cancel themselves out and thus do not contribute much to distortion.



Harmonics originate as currents but generate harmonic voltages as they flow through the impedances in the system. While investigating any problems which may be due to harmonics knowing the harmonic spectrum of the signal is of utmost importance as harmonic spectrum displays the magnitudes of various harmonics constituted in the distorted signal.

Total Harmonic Distortion is the ratio of the power of harmonic components to the power of fundamental frequency component. It is used to measure the wave-shape distortion of original wave.It gives a good estimate of how much energy is wasted when the distorted waveform is applied across a resistive load.

Systems which use non-linear devices, all contribute to creation of harmonics. Uninterruptible power supplies, Microcontroller based devices and variable speed motor drives which are indispensable to the industry are main contributors to harmonics. Domestic appliances like TV sets, Air Conditioners, Washing Machines, Vacuum cleaners, FAX machines and printers also contribute to harmonics.



(Harmonics Cause and Effects, David Chapman)

EFFECTS OF HARMONICS

When non-linear loads constitute more than 20% of the load in a facility, harmonics generated can threaten to disrupt smooth functioning of the facility. Current harmonics can cause issues with distribution equipment and other components of the power system but generally do not cause any problems to the equipment using the supply. They may also lead to excessive heating of transformers.

Voltage harmonics on other hand can affect the equipment connected to the system. Voltage harmonics are able to create sags in voltage supply. The amount of sag depends upon many factors like impedance and wire size. These harmonics thus result into,

- Conductor Over-heating : This problem occurs mainly with neutral conduction in 3 phase systems. Due to imbalance in current caused due to harmonics, despite even harmonics components cancelling each other, the odd harmonics flow through the neutral wire.
- Capacitors : Due to increase in power loss, the capacitor often gets over-heated and it reduces the life of capacitor. If a capacitor is in tune with one of the harmonics then it may lead to dielectric failure.
- Circuit-Breakers : May lead to false tripping of residual current circuit breakers(RCCB). It may lead to spurious operation or trips, which could damage or blow the components for no apparent reasons.

- Transformers and Generators : have increased iron and copper losses which lead to heating of the windings. Sizing and designing thus becomes increasingly important

To mitigate or control the harmonics some measures are: reduce the harmonics of the load, but this is not always possible; Add filters to block the harmonic current from propagating in system; modify the frequency response of filters, capacitors and inductors in the circuit.

However, for any of these methods to be implemented, a system which can accurately measure amplitude of harmonics present is needed. This system should not only be accurate but also be fast and must respond quickly to fluctuations in real time. Such a system would not only help us minimize the losses due to harmonics but would also enable us to have a Distortion Based Tariff System. It would help penalize sources which introduce harmonics and those sources would either have to improve their technology to minimize the harmonics or pay the penalty for introducing them and for their share in distortion of the signal.

Harmonics Analysis using FFT

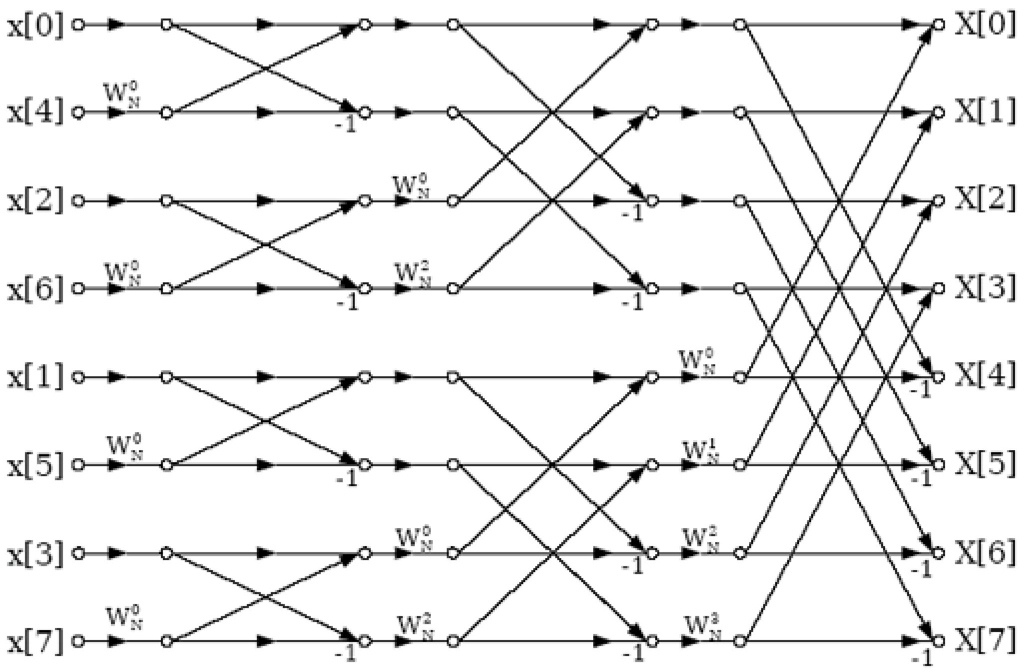
The presence of Harmonics can be detected simply by an oscilloscope but to determine the magnitude of each harmonic present, a detailed analysis of distorted signal is necessary. It further leads us to many measurements, together clumped into Power Indices which give an idea of how closely the signal resembles an ideal signal. For our analysis, we have chosen Fast Fourier Transform (FFT) which is among the most popular and computationally simple processes to analyze a signal.

Fast Fourier Transform

Fast Fourier Transform is an algorithm which is used to compute the Discrete Fourier Transform of a sequence. It has been used to calculate frequency components of signals. It requires data of at least one cycle of input cycle to produce a result however, those results are not accurate for one cycle of time-varying signals. The IEC 61000-4-7 [4] recommends use of FFT for estimation of harmonics considering minimum ten cycles window for 50Hz signals. A major disadvantage of the FFT is that it suffers from spectral leakage. To overcome this problem use of Wavelet Transform or its modified versions is suggested.

The Cooley-Tukey algorithm is amongst the most popular ways to generate FFT of a signal. It recursively breaks down DFT of any composite size ($N=N_1N_2$) into N_1 DFTs of smaller size which is N_2, thereby reducing the computation time to O (N log (N)) for highly composite N.

A radix 2 FFT is simplest and widely used form of the Cooley-Tukey algorithm. A radix 2 FFT divides the N sized FFT into two interleaved DFTs of size N/2 for each size until reduced to the simplest form. Which makes its implementation possible only when $N = 2^p$ that is when N is a power of 2. It can be performed either by Decimation In Time (DIT) approach or Decimation In Frequency (DIF) approach. Here, we have used the DIT approach.



For $N = 2^p$ stages,

Required decimation stages = $p = \log_2 N$

Total Number of complex multiplications = $(N/2)*(\log_2 N)$

Number of complex addition is $N\log_2 N$.

In our context, at sampling frequency (F_s) = 1600 Hz, and with input signal being a sinusoidal wave of fundamental frequency 50 Hz, we obtain 32 samples from one cycle of the input signal. As suggested by IEC 61000-4-7[4] standards, we will have to consider at least 10 cycles which is equivalent to operating on 320 samples of data. However, due to limitations of the radix 2 algorithm, we have considered processing on data obtained from 512 point FFT (16 cycles) and data obtained from 256 point FFT (8 cycles) for empirical purposes.

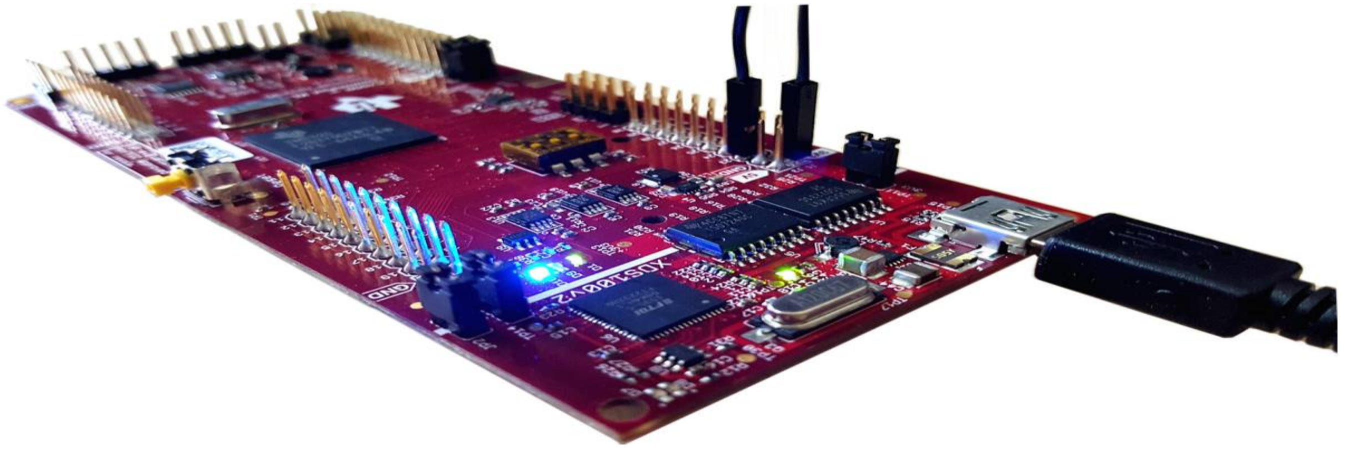
For 256 point FFT frequency resolution = 6.25Hz

For 512 point FFT frequency resolution = 3.125 Hz

Harmonics/Frequency	Corresponding Index in 256 point FFT	Corresponding Index in 512 point FFT
DC Component (0Hz)	X[0]	X[0]
Fundamental Frequency (50Hz)	X[8]	X[16]
3rd Harmonic (150Hz)	X[24]	X[48]
5th Harmonic(250Hz)	X[40]	X[80]
7th Harmonic(350Hz)	X[56]	X[112]
9th Harmonic(450Hz)	X[72]	X[144]

To compensate the error due to spectral leakage, while calculating the magnitude corresponding to each index in the FFT, we have also considered the magnitudes of indices adjacent to corresponding points.

For the purpose of analyzing and implementation of the discussed algorithm, we have used Texas Instrument's LAUNCHXL-TMS320f28379D development board. The JTAG feature enables easy debugging and programming of the Digital Signal Controller. The software used to program is Code Composer Studio v8.0 IDE developed by Texas Instruments.



The LAUNCHXL-TMS320f28379D LaunchPad features include:

- USB debugging and programming interface via a high-speed galvanically isolated XDS100v2 debug
- probe featuring a USB/UART connection

- Superset TMS320F28379D device
- Two user LEDs
- Device reset pushbutton
- Easily accessible device pins for debugging purposes or as sockets for adding customized extension boards
- Dual 5 V quadrature encoder interfaces
- CAN Interface with integrated transceiver
- Boot selection switches
- Differential Amplifier to provide buffered signals to ADCD for 16-bit mode
- Optional SMA connection points P/N:SMA-J-P-H-ST-EM1
- Four Sigma Delta demodulator inputs brought to the BP headers

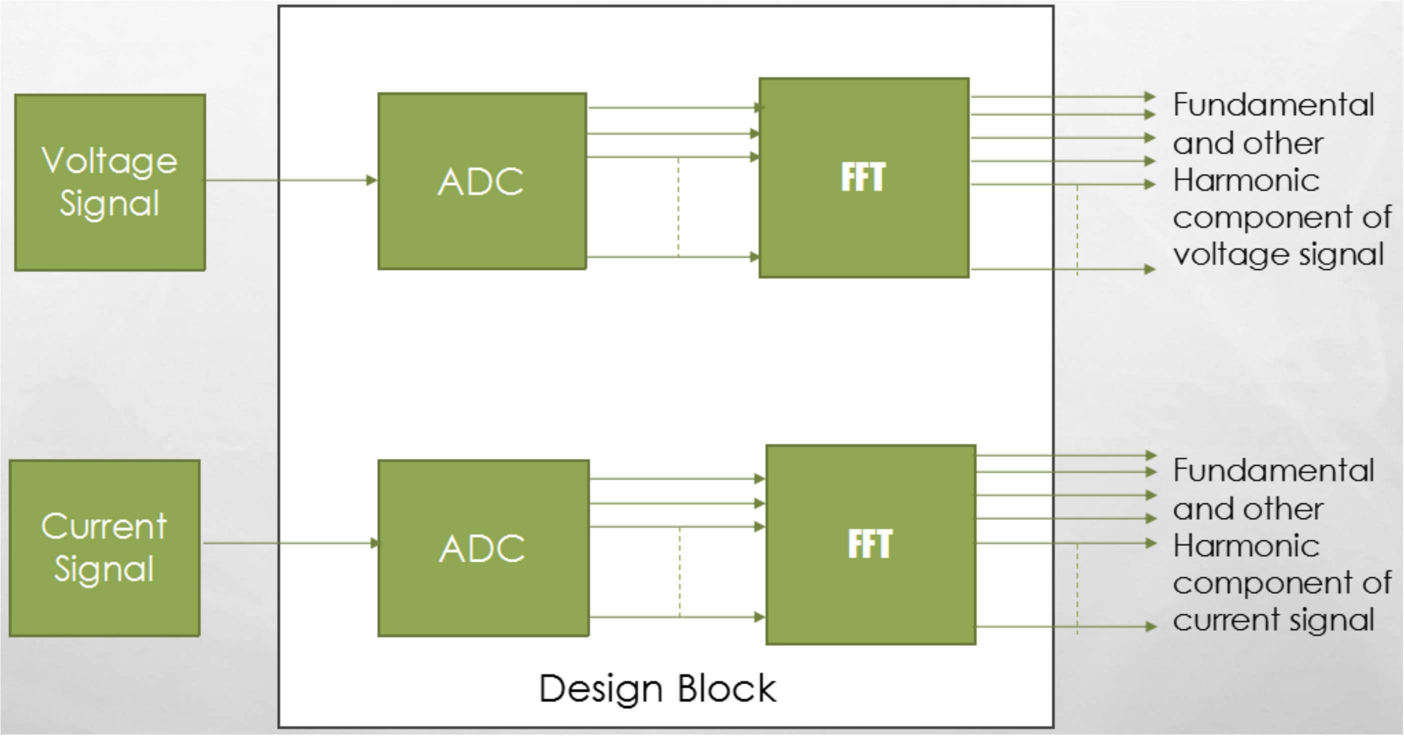
It is a dual core processors function at frequency of 100MHz. It has three 12-bitADCs which work only on unipolar signal inputs with respect to zero voltage reference which cannot be changed and one 16-bit ADC whose reference can be changed. Sampling frequencies of these ADCs depend on ePWMs generated internally. By manipulating the ePWMs we have used two 12-bit ADCs to sample the Voltage as well as Current signal at the frequency of 1600 Hz. The maximum permissible magnitude for an input to these ADCs is 3V. Thus for purposes suitable to our implementation, input is a distorted waveform of fundamental frequency 50Hz, peak to peak Voltage less than 3V and with a DC offset equal to half of peak to peak voltage.

IMPLEMENTATION

The implemented design will not only have to accurately measure the amplitudes of harmonics present but also function in real time and continuously analyze the input signals to give consistent results over time. Along with amplitude of current and voltage, another criterion considered for validating the accuracy of design is Total Harmonic Distortion (THD) as it is one of the important measurements in power systems.

Before implementing the design on the Digital Signal Controller, it was implemented on MATLAB to understand and get a general idea of the processes and calculations involved. The results obtained from MATLAB were in accordance with theoretically expected values and are thus considered theoretical results and are considered as the reference for all error calculations performed on the experimentally obtained results.

BLOCK DIAGRAM



The sampling frequency (F_s) for ADCs used is set to 1600 Hz. A frequency lower than this would reduce our number of samples per wave, making the process less accurate while increasing frequency would make it more accurate but increase the complexity of the process. At 1600Hz frequency 32 samples are obtained from each cycle of sinusoidal wave of fundamental frequency 50Hz. The IEC standards require us to sample a minimum of 10 cycles for estimation, which would mean processing a minimum of 320 samples. Due to limitation imposed by Radix-2 algorithm, we cannot use 320 samples as 320 is not a power of 2. Thus, for empirical purposes we have calculated FFTs for 256 samples (8 cycles) and 512 samples (16 cycles) which are closest powers of 2 less than and greater than 320.

Every 2^N point FFT will take N stages in radix-2 to algorithm. Since we have two FFTs a memory equivalent to 2N stages would be required. To optimize the memory requirements and avoiding usage of externally attached memory, ping-pong architecture is used.

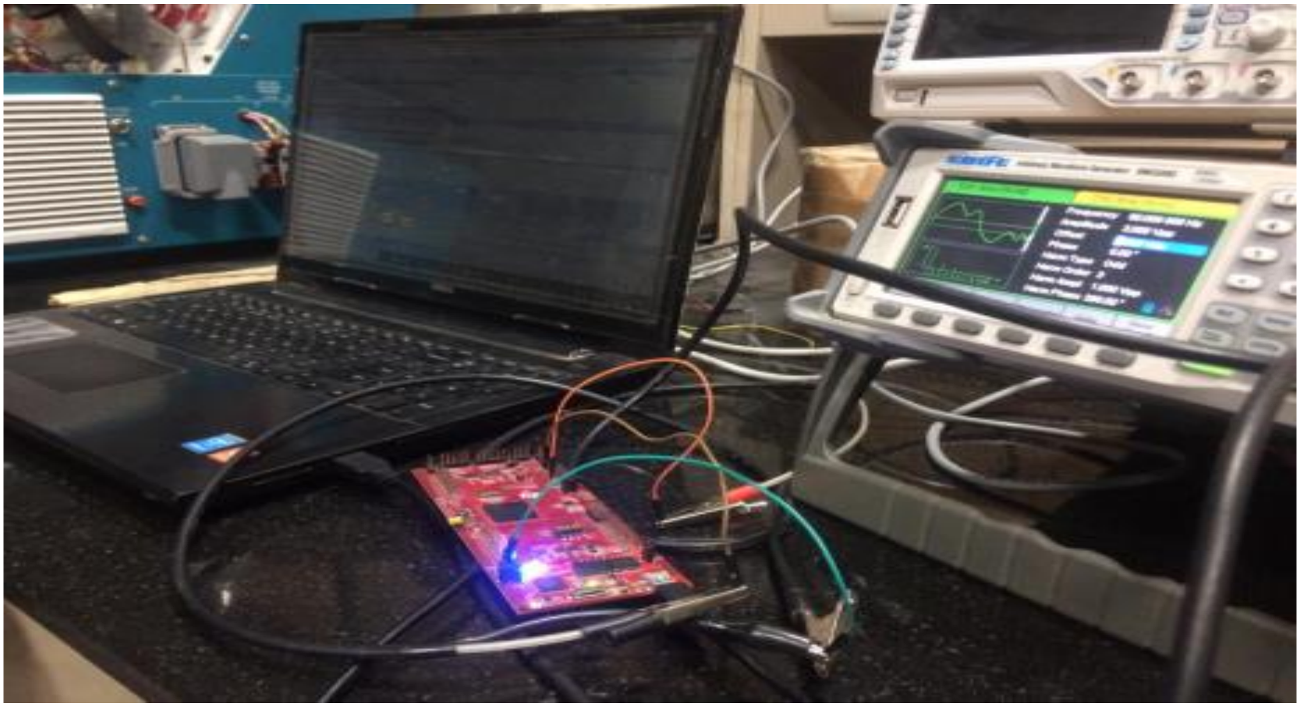
The FFT suffers from spectral leakage in case of real-time non-stationary signals. The formula used to estimate amplitude from the FFT measurements is modified to consider the spectral leakage and provide us a more accurate measurement of the amplitude.

Due to limitations of the ADCs in Digital Signal Controller, we cannot obtain the samples for a bipolar signal. The maximum voltage which is sampled is 3V at max. Thus, peak to peak voltage of any input signal cannot be more than 3 Volts. And every input should have a DC-offset voltage which is equal to half of its peak to peak voltage.

Each input signal is then sampled at a frequency of 1600 Hz and the sampled data is processed using the radix-2 FFT algorithm which then provides us with the output of FFT. This FFT output is then processed to calculate the amplitudes of harmonics present and total harmonic distortion(THD).

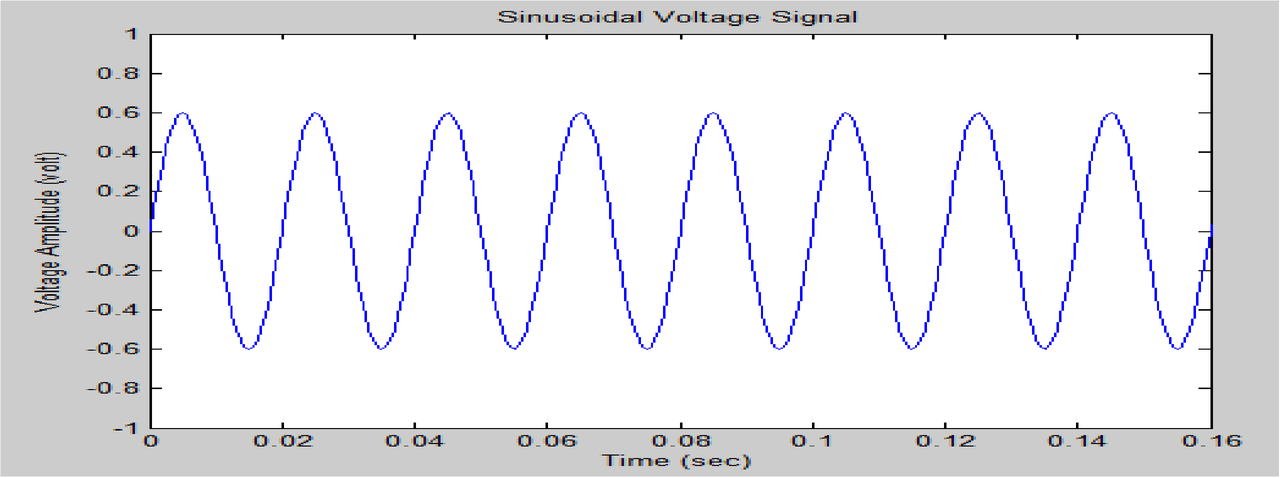
To ensure that the implemented design and logic is consistent, first current as well as voltage signal for the experimental analysis was taken to be a sinusoidal wave. Then harmonics were introduced and for final case a square wave was considered as voltage signal and current input was a sinusoidal wave with harmonics.

To generate these signals, Arbitrary Waveform Generator SMG2082 developed by SCIENTIFIC INSTRUMENTS, was used.



CASE 0:

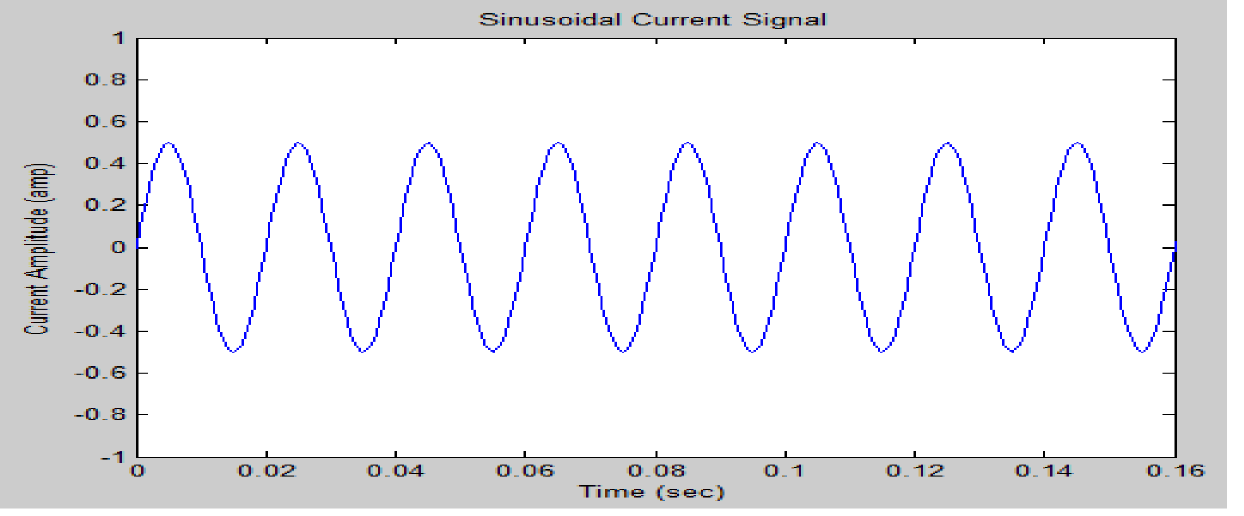
Voltage Input



Waveform : Sinusoid (50Hz, 0.600V Amplitude)

Harmonics : Not Present

Current Input

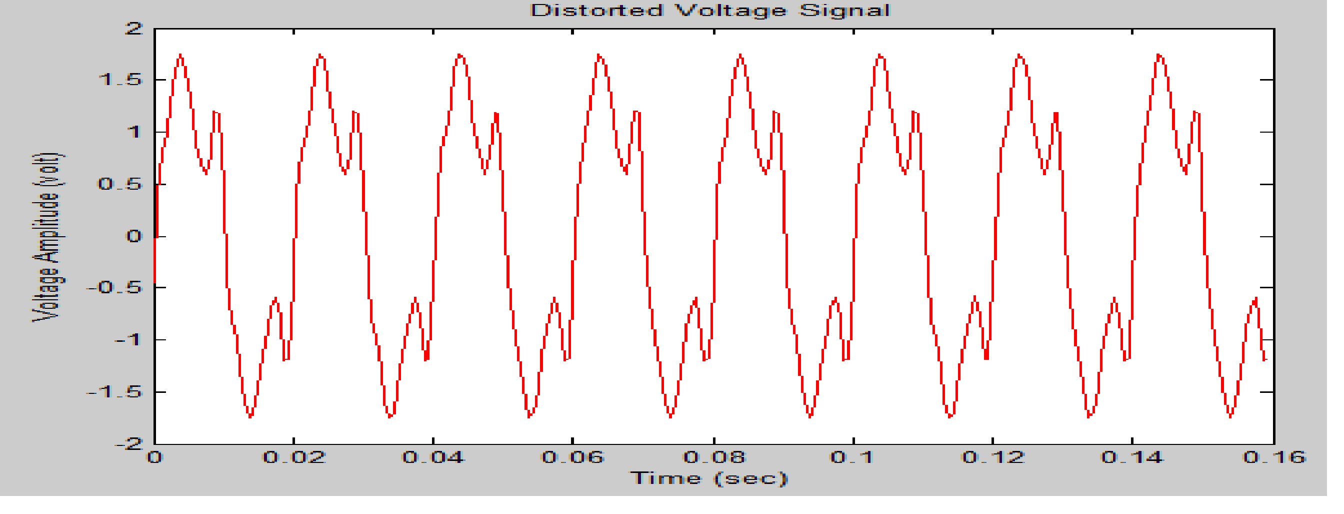


Waveform : Sinusoid (50Hz, 0.500V Amplitude)

Harmonics : Not present

CASE 1:

Voltage Input

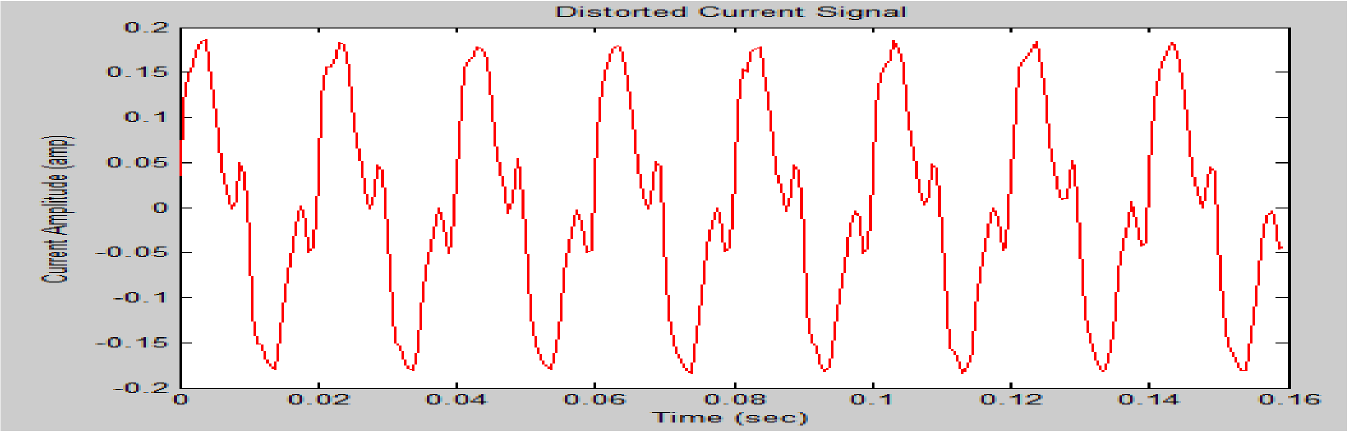


Waveform : Sinusoid (50Hz, 1.500V Amplitude)

Harmonics : 3rd Harmonic (150Hz, 0.500V), 5th Harmonic (250Hz, 0.250V),

7th Harmonics (350Hz, 0.150V), 9th Harmonic (450Hz, 0.050V).

Current Input



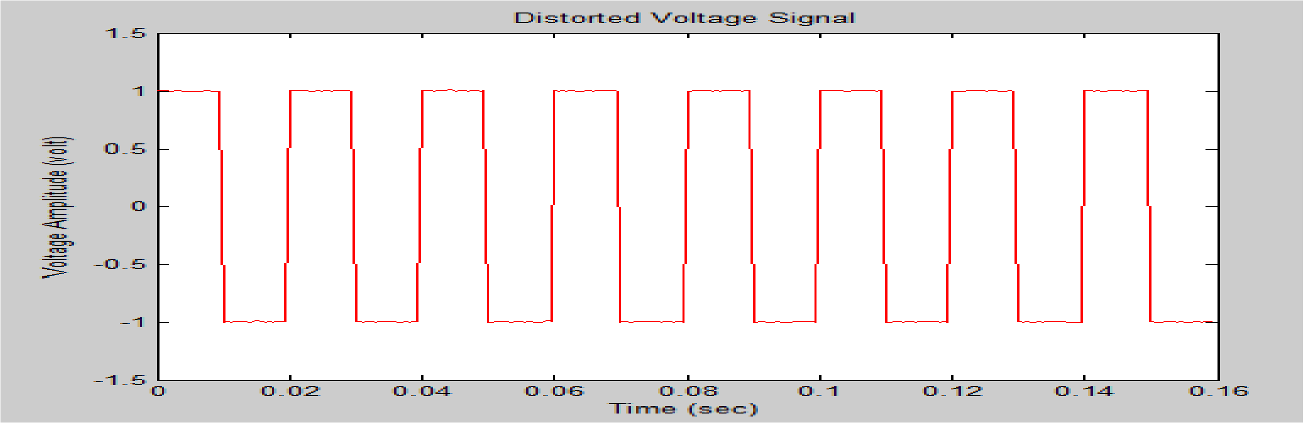
Waveform : Sinusoid (50Hz, 0.150V Amplitude)

Harmonics : 3rd Harmonic (150Hz, 0.050V), 5th Harmonic (250Hz, 0.025V),

7th Harmonics (350Hz, 0.015V), 9th Harmonic (450Hz, 0.005V).

CASE 3:

Voltage Input



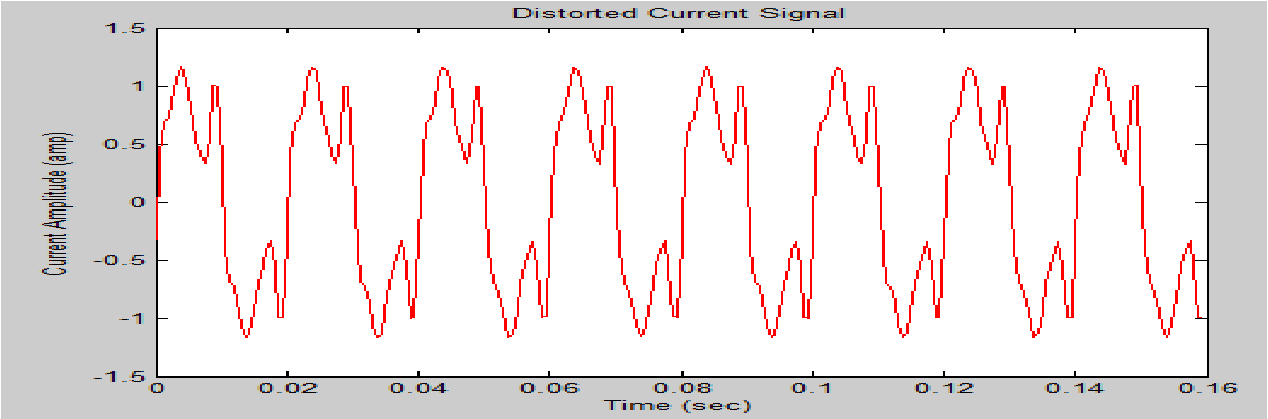
Waveform : Square Wave (50Hz, 1.000V Amplitude)

Harmonics : Fundamental (50Hz, 1.273V), 3rd Harmonic (150Hz, 0.424V),

5th Harmonic (250Hz, 0.255V), 7th Harmonic (350Hz, 0.182V),

9th Harmonic (450Hz, 0.141V).

Current Input



Waveform : Sinusoid (50Hz, 1.000V Amplitude)

Harmonics : 3rd Harmonic (150Hz, 0.400V), 5th Harmonic (250Hz, 0.250V),

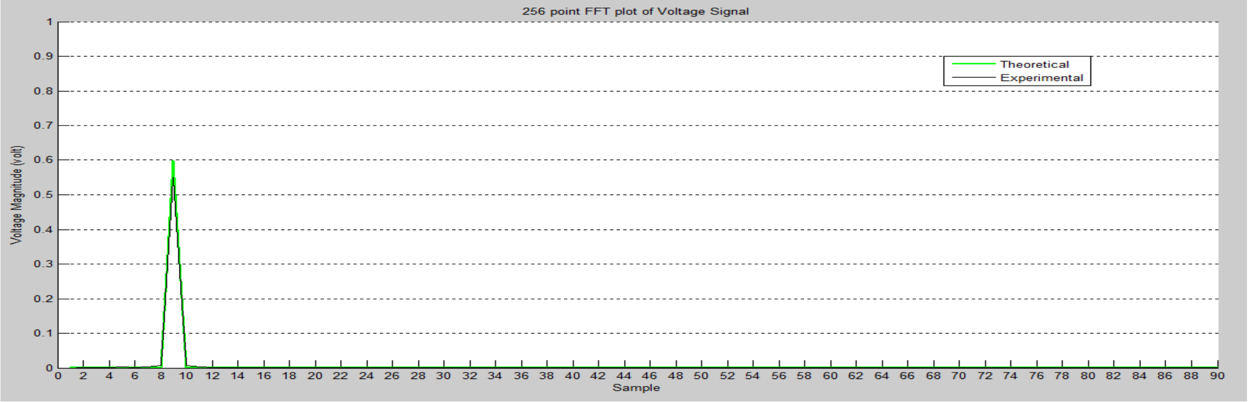
7th Harmonics (350Hz, 0.150V), 9th Harmonics (450Hz, 0.050V).

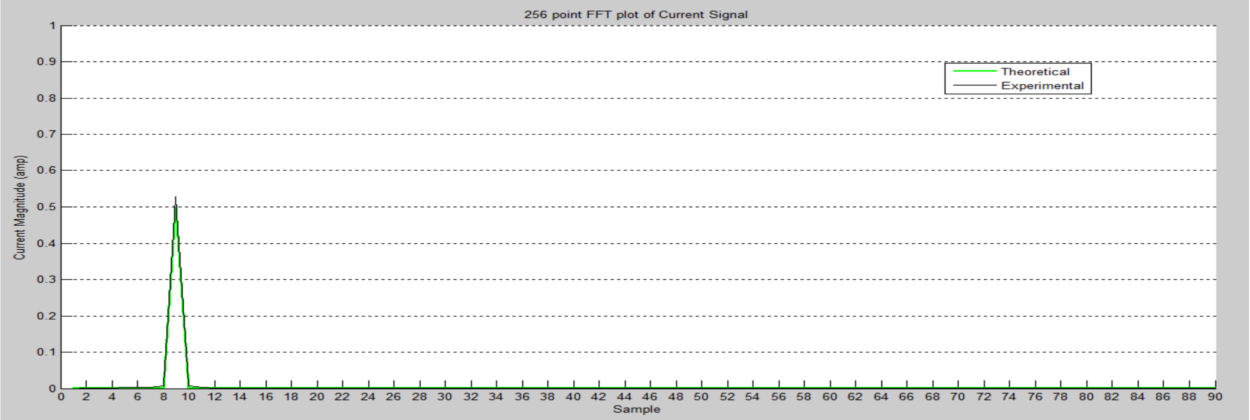
EXPERIMENTAL RESULTS

To verify our observation, we considered results implemented from the MATLAB as reference values. To account for the noise, noise was added to the signal processed in MATLAB. FFT output was calculated and plotted for both 256-point FFT as well as 512-point FFT from MATLAB. On same graph, results obtained using the algorithm were also plotted to directly compare them. Further, amplitude of Harmonics was found out and it was found that the algorithm implemented gave results in accordance to the results expected from MATLAB.

CASE 0:

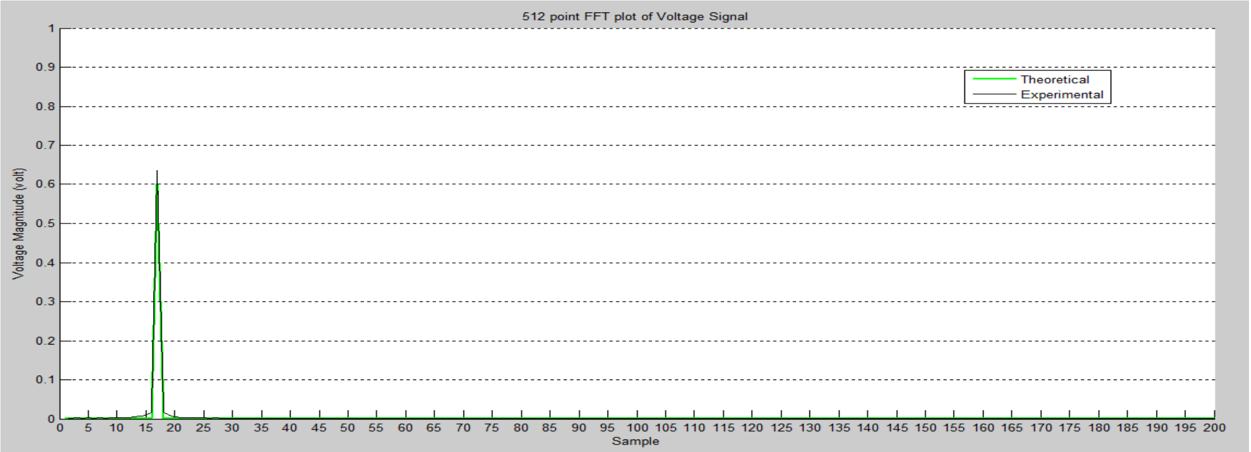
Following is the 256-point FFT plot for case 0.

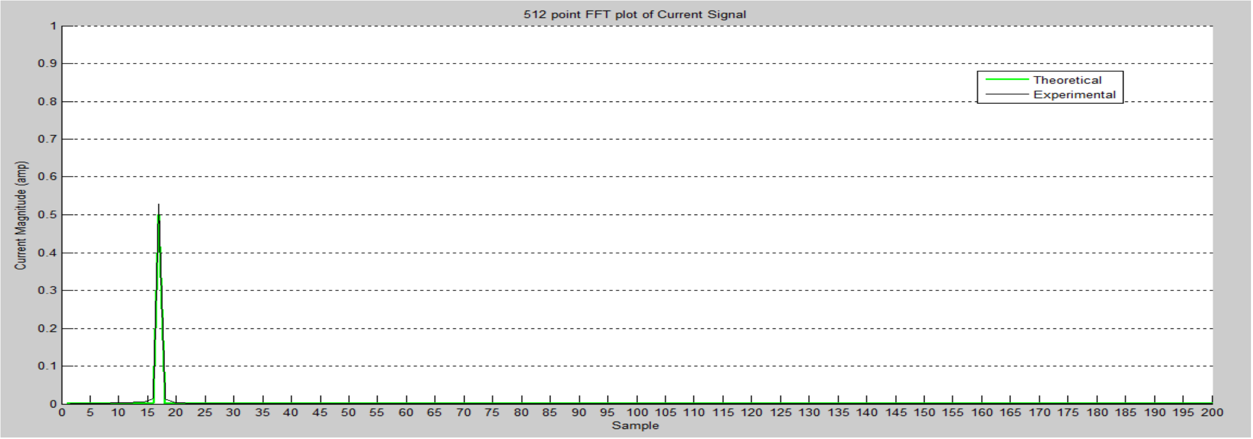




As we can see, the graphs are as we expect them to be for pure sinusoids. Value corresponding to sample 8th determines the voltage for frequency component in 256- point case.

For 512-point FFT,





These figures clearly tell us that for mere FFT, 512-point FFT is more accurate than 256-point FFT. In this case, magnitude corresponding to 50 Hz is obtained from the value of 16^{th} sample.

The values obtained from MATLAB are considered to be the theoretical values and those obtained from the algorithm are called as experimental values.

Following is a tabular version of observations for CASE 0,

256-point FFT

	Theoretical	Experimental	Relative Error(%)
Voltage (V)	0.600	0.550	8.33
Current(A)	0.500	0.529	5.70

512-point FFT

	Theoretical	Experimental	Relative Error(%)

Voltage (V)	0.6000	0.6345	5.75
Current (A)	0.5000	0.5276	5.52

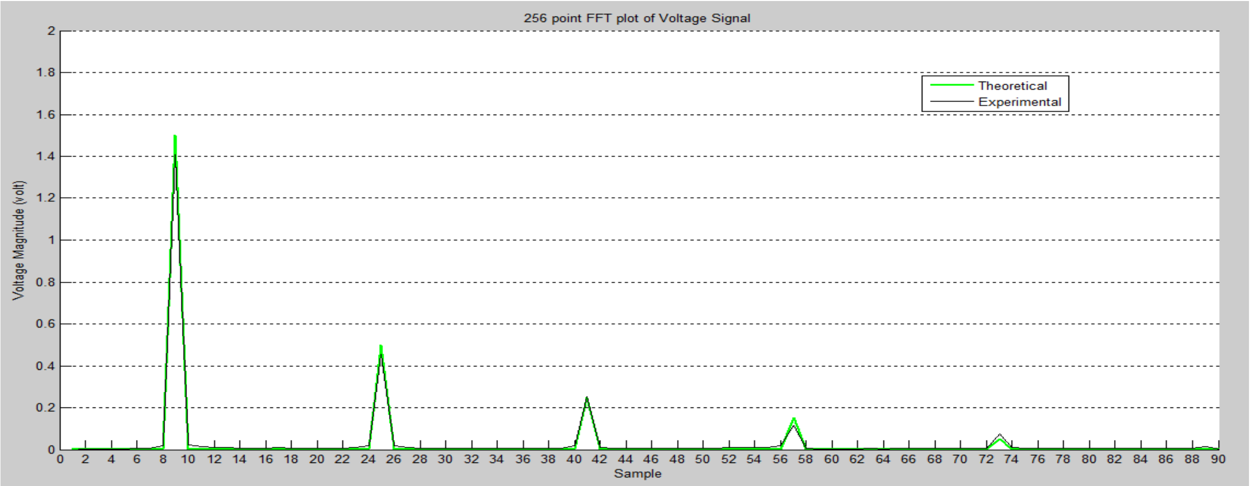
From relative error values obtained, it is clear that 512-point FFT is superior in calculating the amplitude for pure sinusoids.

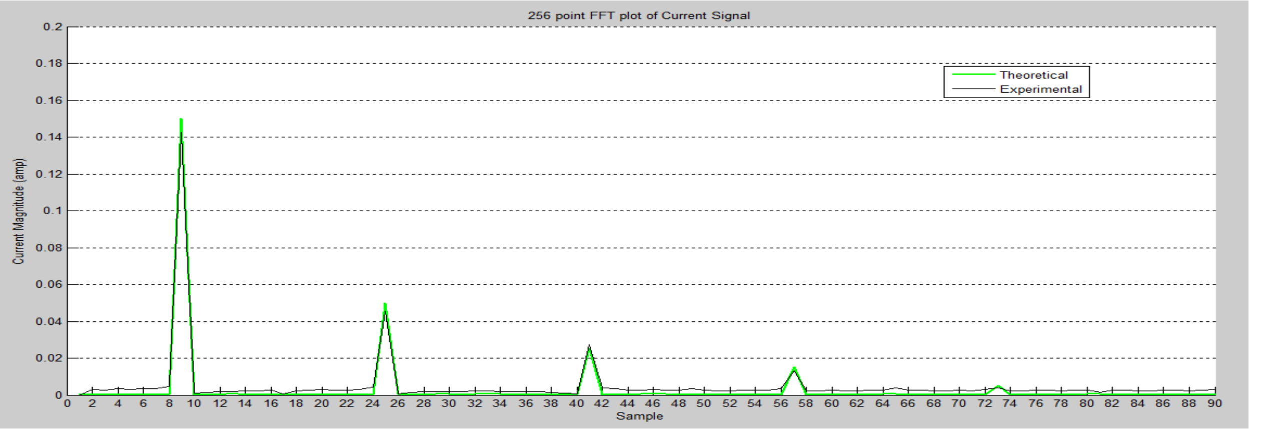
CASE 1:

The distorted signal input from the Arbitrary Waveform Generator (AWG) was,

Harmonic Order	Voltage(V)	Current(A)
Fundamental	1.5000	0.1500
3rd	0.5000	0.0500
5th	0.2500	0.0250
7th	0.1500	0.0150
9th	0.0500	0.0050

On analysis using FFT, we obtained following plots for 256 point FFT,





We expect peak at 8th sample to inform us about magnitude of the fundamental frequency.

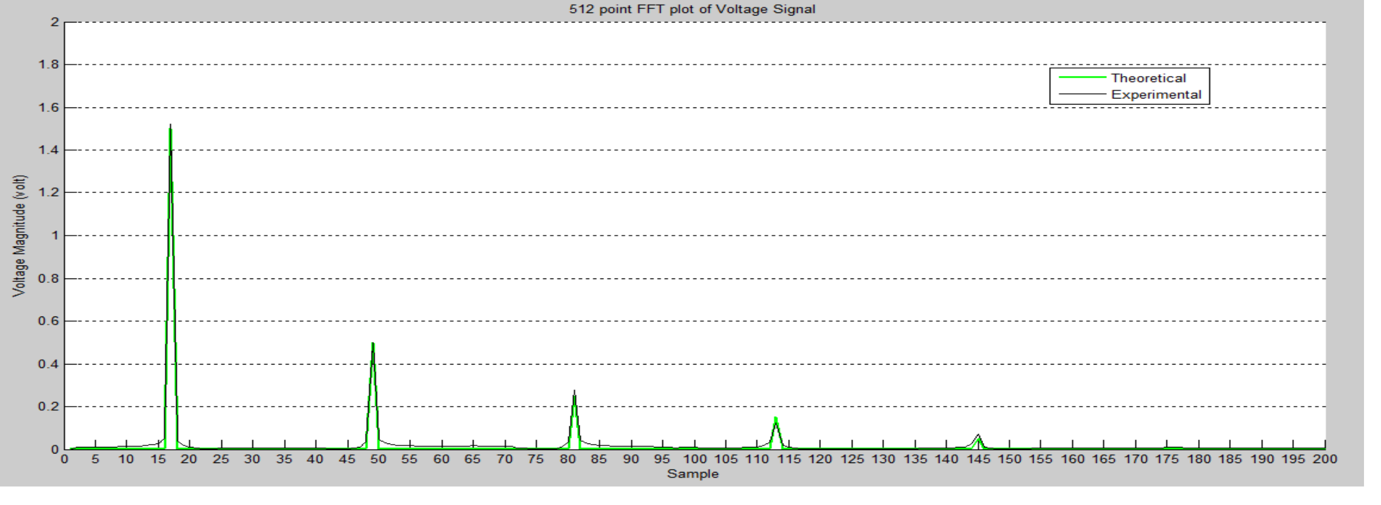
The 24th sample corresponds to frequency of 3rd Harmonic which is 150 Hz.

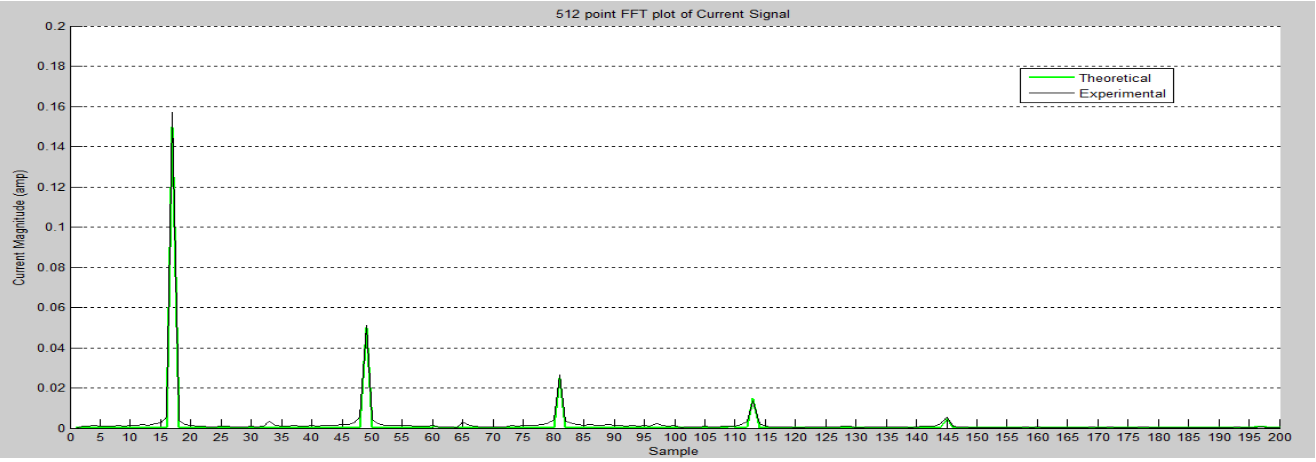
The 40th sample corresponds to frequency of 5th Harmonic which is 250 Hz.

The 56th sample corresponds to frequency of 7th Harmonic which is 350 Hz.

The 72nd sample corresponds to frequency of 9th Harmonic which is 450 Hz.

And following plots for 512-point FFT,





We expect peak at 16th sample to inform us about magnitude of the fundamental frequency.

The 48th sample corresponds to frequency of 3rd Harmonic which is 150 Hz.

The 80th sample corresponds to frequency of 5th Harmonic which is 250 Hz.

The 112th sample corresponds to frequency of 7th Harmonic which is 350 Hz.

The 144th sample corresponds to frequency of 9th Harmonic which is 450 Hz.

Following tables represents values obtained for 256-point FFT

Harmonic Order	Voltage(V)			Current(A)		
	Theoretical	Experimental	Relative Error(%)	Theoretical	Experimental	Relative Error(%)
Fundamental	1.5004	1.4136	5.79	0.1496	0.1425	4.75
3rd	0.5003	0.4550	9.05	0.0499	0.0455	8.82
5th	0.2499	0.2539	1.60	0.0255	0.0276	8.24
7th	0.1499	0.1183	21.08	0.0147	0.0149	1.36
9th	0.0501	0.0779	55.48	0.0055	0.0068	23.64

THD_V (Theoretical) = 38.74% THD_V (Experimental) = 36.54%   Relative Error in THD_V= 5.78%

THD_I (Theoretical) = 38.87% THD_I (Experimental) = 38.73%   Relative Error in THD_I= 0.36%

For 512-point FFT

Harmonic Order	Voltage(V)			Current(A)		
	Theoretical	Experimental	Relative Error(%)	Theoretical	Experimental	Relative Error(%)
Fundamental	1.5003	1.5524	3.47	0.1498	0.1425	4.53
3^{rd}	0.4998	0.4941	1.14	0.0499	0.0455	3.81
5^{th}	0.2499	0.2738	9.56	0.0249	0.0276	7.23
7^{th}	0.1500	0.1282	14.53	0.0148	0.0149	4.05
9th	0.0503	0.0750	49.11	0.0055	0.0061	10.91

THD_V (Theoretical) = 38.71% THD_V (Experimental) = 38.47%   Relative Error in THD_V= 0.62%

THD_I (Theoretical) = 38.71% THD_I (Experimental) = 38.51%   Relative Error in THD_I= 0.52%

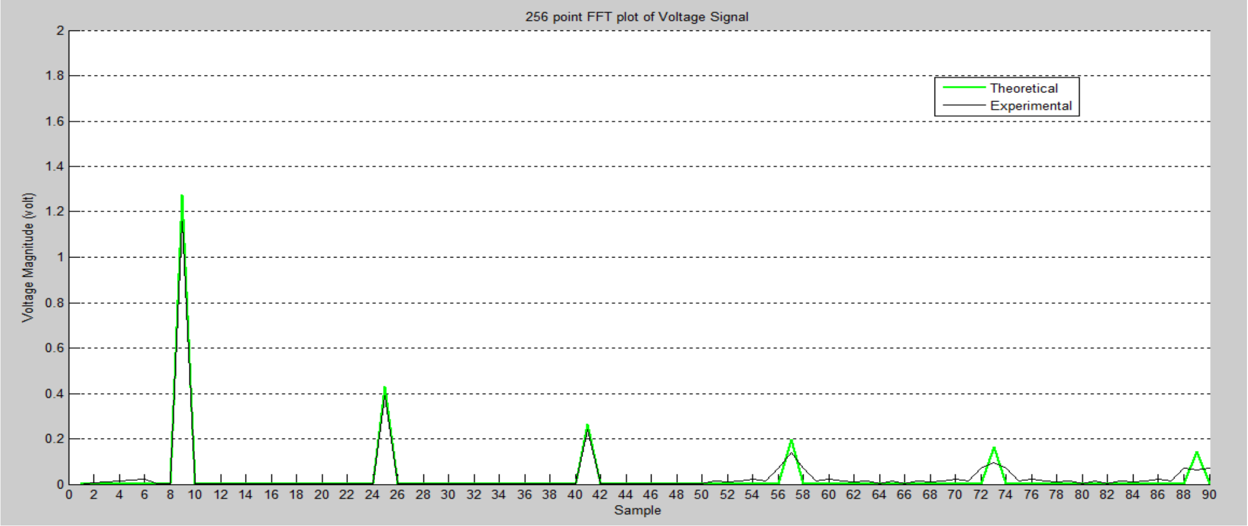
In this case too, for majority of values, a 512-point FFT provides better results than the ones obtained from 256-point FFT.

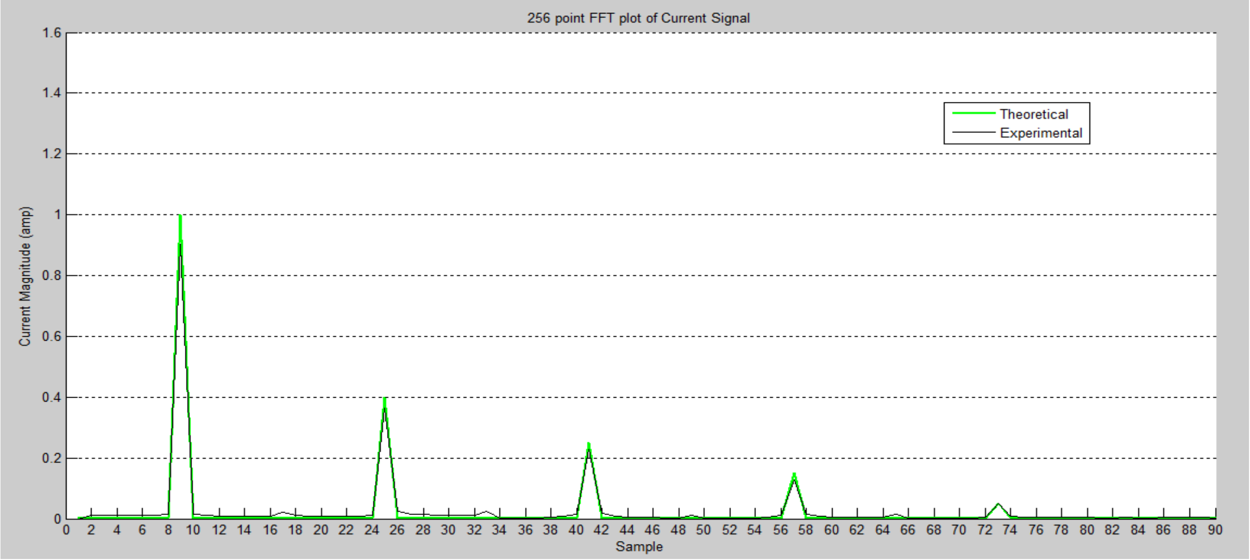
CASE 3:

In this case, our distorted input signal details are

Harmonic Order	Voltage(V)	Current(A)
Fundamental	1.273	1.000
3^{rd}	0.424	0.400
5^{th}	0.255	0.250
7^{th}	0.182	0.150
9^{th}	0.141	0.050

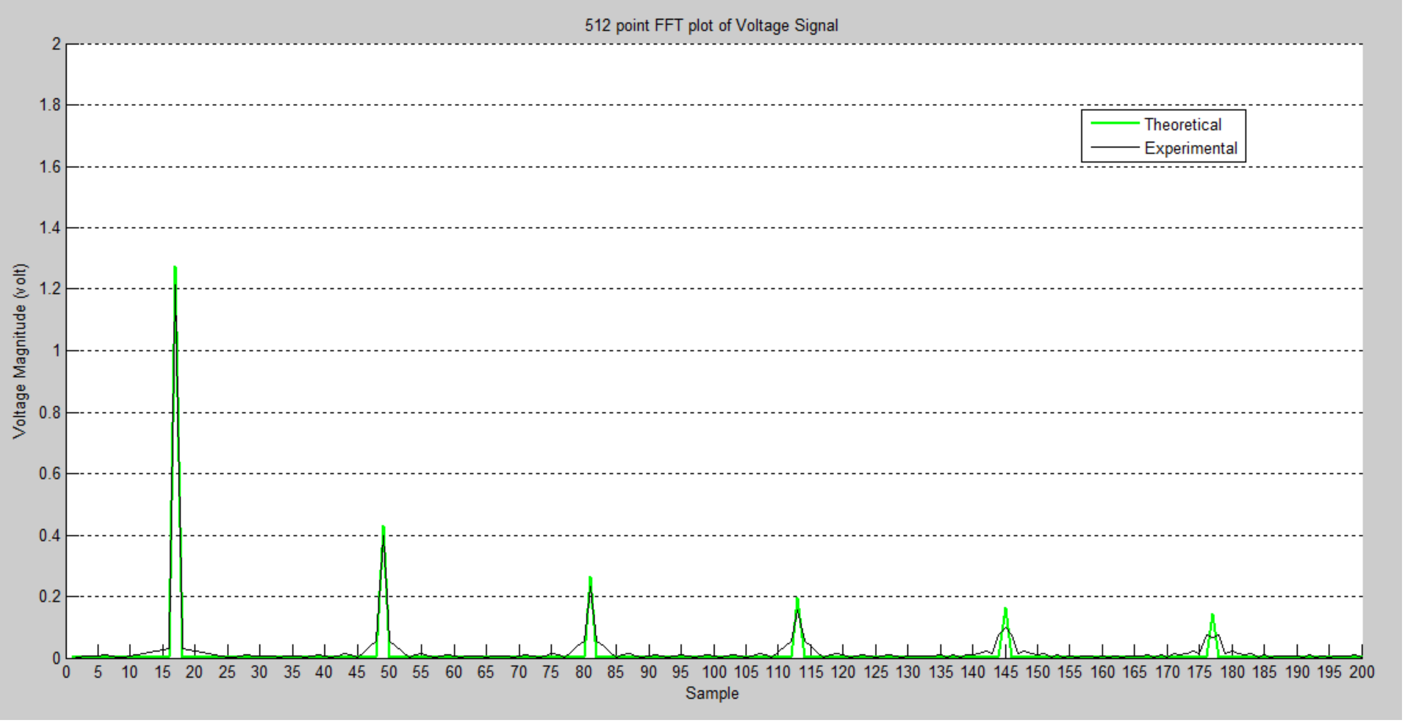
256-point FFT plots are

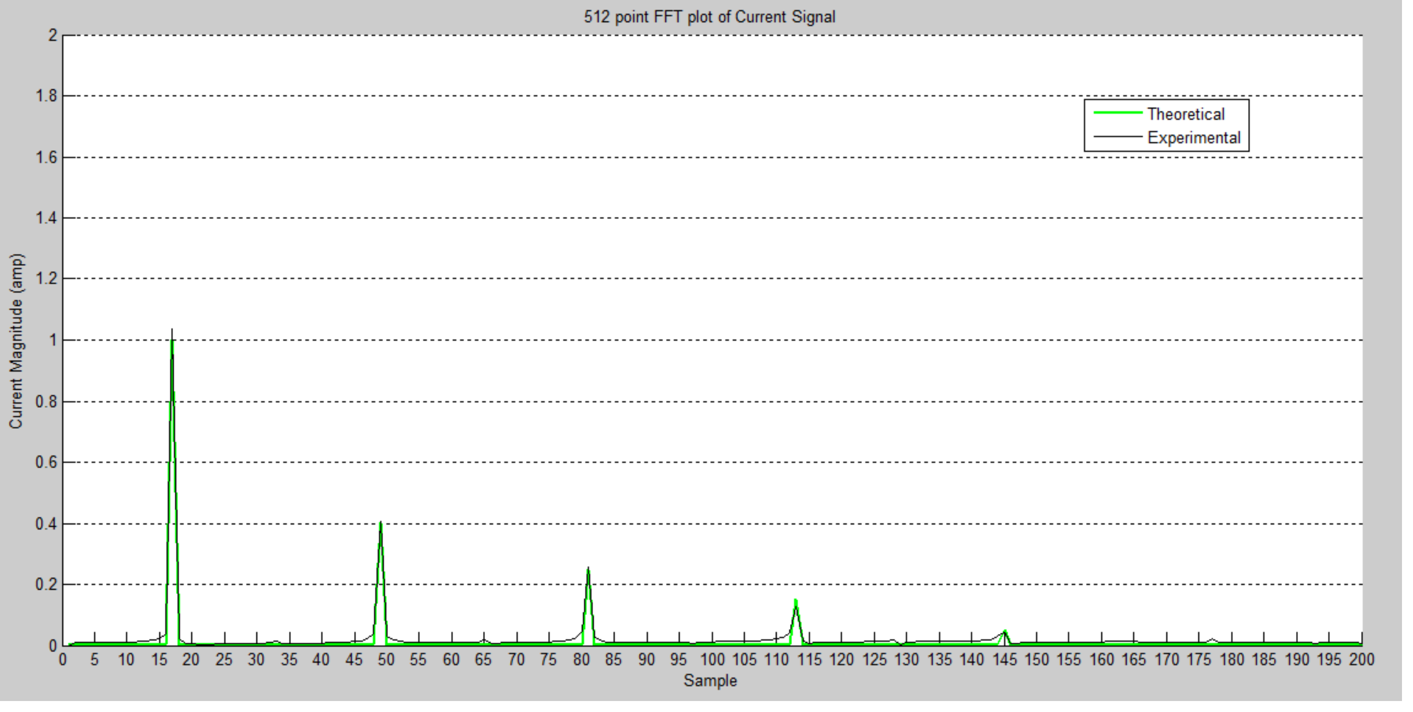




FFT plot for voltage signal at higher samples shows a large deviation from the expected nature. However, expected peak remains same.

512-point FFT plot is





We see similar deviation in higher samples for the Voltage signal as we see in 256-point FFTs.

More results are as follows,

For 256-point FFT

Harmonic Order	Voltage(V)			Current(A)		
	Theoretical	Experimental	Relative Error(%)	Theoretical	Experimental	Relative Error(%)
Fundamental	1.2751	1.1585	9.14	1.0001	0.9030	9.71
3^{rd}	0.4301	0.3881	9.77	0.3998	0.3638	9.00
5^{th}	0.2647	0.2262	14.54	0.2501	0.2278	8.92
7^{th}	0.1973	0.1726	12.52	0.1501	0.1271	15.32
9th	0.1621	0.1384	14.62	0.0498	0.0515	3.41

THD_V (Theoretical) = 44.38% THD_V (Experimental) = 43.23%   Relative Error in THD_V= 2.59%

THD_I (Theoretical) = 49.74% THD_I (Experimental) = 49.34%   Relative Error in THD_I= 0.80%

For 512-point FFT

Harmonic Order	Voltage(V)			Current(A)		
	Theoretical	Experimental	Relative Error(%)	Theoretical	Experimental	Relative Error(%)
Fundamental	1.2752	1.2136	4.83	1.0001	1.0348	3.45
3^{rd}	0.4306	0.3987	7.41	0.3998	0.4044	1.05
5^{th}	0.2648	0.2415	8.80	0.2501	0.2590	3.60
7^{th}	0.1973	0.1792	9.17	0.1501	0.1474	1.67
9th	0.1618	0.1428	11.74	0.0498	0.0646	28.43

THD_V (Theoretical) = 44.41% THD_V (Experimental) = 43.79%   Relative Error in THD_V= 0.62%

THD_I (Theoretical) = 49.77% THD_I (Experimental) = 49.94 % Relative Error in THD_I= 0.34%

The square deviation in FFT plot of voltage signal can be attributed to the nature of the input signal.

As we can see, even in this case, a 512-point FFT provides results closer to the expected ones. Not only for measurement of Amplitude but also for measurement of THD.

Conclusion

The Algorithm has been simulated on MATLAB and successfully implemented on the Digital Signal Controller and the results obtained were in accordance with the results obtained from MATLAB.

A 512-point FFT gives more accurate estimation of Harmonic Amplitudes than a 256-point FFT for most of the Harmonics considered.

For parameters like THD, a 512-point FFT seems to be more accurate. Determining more power Indices using both these would help decisively conclude which among them provides accurate results for most.

Once the harmonics are detected the power quality indices can be calculated.

Suitable methods can be applied to mitigate harmonics.

This design can take us a step closer to distortion based tariff realisation.

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