YAŞAR UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

MASTER THESIS

WAVELET BASED HARMONIC ANALYSIS: CASE STUDY OF A PLANT WITH COGENERATION

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of master of science.

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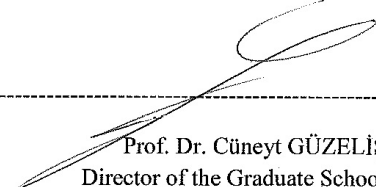
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ABSTRACT

WAVELET BASED HARMONIC ANALYSIS: CASE STUDY OF A PLANT WITH COGENERATION

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Industrial countries constitute energy policies in order to decrease energy gap and minimize environmental issues. Increasing use of renewable energy sources and with the expansion of using distributed generation is the solutions to energy related problems in our country. A cogeneration system is a distribution generation unit which supplies electrical and heat demand of the developing industry. These systems are more preferable due to its higher efficiencies against separate generation systems and lower environmental impact. The cogeneration system which analyzed in this thesis is installed in İzmir and fed 3 different loads. It connects to interconnection point via point common coupling which can be used in case the cogeneration switches to island mode.

In the first part of this study, the harmonic components of different operating modes of a cogeneration system are analyzed. Since wavelet based algorithm tracks harmonics effectively and gives in time frequency spectrum, the wavelet theory is used among the methods covered in literature to find harmonics. Studies have been conducted to choose a mother wavelet. This analysis is aimed to determine the direction of harmonic flow on both gas turbines and loads. In the second part, low-pass filters and de-noising algorithm are used to decrease the effect of harmonics. It is observed that wavelet based global thresholding decrease harmonics effectively.

In the last part of the study; comparisons are made between designed low-pass filter and de-noising algorithm with wavelets. Depending on the selected mother wavelet, de-noising algorithm is found to be quite successful when eliminating harmonics

Keywords: Wavelet analysis, power system harmonics, global threshold, denoise

ÖZET

DALGACIK TABANLI HARMONİK ANALİZİ: KOJENERASYON SİSTEMLİ BİR ÖRNEK OLAY İNCELEMESİ

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Sanayi ülkelerinde enerji açığını azaltmak ve çevresel sorunları en aza indirgemek amacıyla çeşitli enerji politikaları oluşturulmaktadır. Yenilenebilir enerji kaynaklarının kullanımının arttırılması ve ayrık üretim sistemlerinin yaygınlaştırılması ile ülkemizde ve dünyada yaşanan enerji sorununa çözüm bulunmaya çalışılmıştır. Bir ayrık üretim sistemi olan kojenerasyon sistemleri gelişmekte olan endüstrinin hem elektrik hem de ısıl ihtiyacını karşılamaktadır. Bu sistemlerin bağımsız olarak ısı ve elektrik üreten tesislere göre daha yüksek verime sahip olması ve çevresel etkilerinin az olması kojenerasyon sistemlerini tercih edilir hale getirmiştir. Bu tezde analiz edilen kojenerasyon sistemi İzmir'de kurulmuş olup; 3 adet yükü beslemektedir. Kuplaj noktası ile enterkonnekte sisteme bağlanarak; gerektiği durumlarda kendini ada durumuna alabilmektedir.

Bu çalışmanın birinci kısmında bir kojenerasyon sistemindeki çeşitli çalışma modlarındaki harmonikler incelenmiştir. Harmonikleri belirlemek için literatürde kullanılan yöntemler içerisinden dalgacık metodu kullanılmıştır. Ana dalgacık seçebilmesi için gerekli çalışmalar yapılmıştır. Dalgacık tabanlı algoritma harmonikleri hızlı bir şekilde tespit ederek frekans zaman spektrumunda vermektedir. Bu analiz, hem türbinler hem de yükler üzerinde gerçekleştirilerek harmoniklerin akış yönünün belirlenmesi amaçlamıştır. Çalışmanın ikinci kısmında ise harmoniklerin etkisini azaltmak için alçak geçirgen filtre ile gürültü süzme algoritması kullanılmıştır. Evrensel eşikleme yöntemi ile harmonikler azaltılarak çıkış sinyali neredeyse giriş sinyaline yaklaşmış; bu şekilde harmoniklerin elenmesi sağlanmıştır.

Çalışmanın son kısmında; Tasarlanan alçak geçirgen filtre ile gürültü süzme algoritması arasında karşılaştırma yapılmıştır. Seçilen ana dalgacığa bağlı olarak

gürültü süzme algoritmasının sistem harmoniklerini eleme konusunda oldukça başarılı olduğu gözlenmiştir.

Anahtar sözcükler: Dalgacık analizi, güç sistemlerinde harmonik, evrensel eşikleme, gürültü süzme

ACKNOWLEDGEMENTS

TEXT OF OATH

I declare and honestly confirm that my study, titled "Wavelet Based Harmonic Analysis: Case Study of a Plant With Cogeneration" and presented as a Master's thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions, that all sources from which I have benefited are listed in the bibliography, and that I have benefited from these sources by means of making references.

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Abbreviations

DG   Distributed generation

CHP   Combined heat and power

FT   Fourier transform

STFT   Short time Fourier transform

DWT   Discrete Wavelet transform

MRA   Multi-resolution analysis

PCC   Point common coupling

UPS   Uninterruptable Power Supply

FIR   Finite Impulse Response

1   INTRODUCTION

European Union sets a target that utilization on renewable energy is increased 20% by 2020. The predominance of this energy will be obtained by distributed generation units. "Distributed generation, on-site generation or decentralized generation is a term describing the production of electricity for use on-site, rather than transmitting energy over the electric grid from a large centralized facility." (Environmental and Energy Study Institute, 2015). Energy efficiency increase significantly when electricity is produced smaller amounts and closer to end-users. It is also reduce carbon pollutions and improve quality of the energy.

Distributed generation (DG) can be used to generate entire electricity supply; for peak shaving; stand-by generation or as a green power source. It is used in many areas such as domestic, commercial, industrial and greenhouses. Generation capacity is ranged from few kilowatts to megawatts. Flexibility, reliability and power quality response make these systems more preferable. It has lower capital costs against big generation systems because of its smaller sizes. It increases power reliability as a back-up or stand-by power system. It lowers the need for large constructions and upgrades in present systems. It is also produce near-zero pollutant emissions with some new technologies like biomass. In a combined heat and power application DG efficiencies rise up to 90% because waste heat can be captured and used to generate electricity. (EPCOR, 2015)

Beside of all these benefits there are some challenges associated with DG systems. DG systems are connected to distribution networks. National standards for interconnection and contractual barriers are not clear for these technologies. They have many requirements for fees and charges. Environmental regulations and larger DG systems make these projects uneconomical. The connection of DG causes some issues because distribution system is designed to feed power from a relatively few large station generations. It is not designed to accept the feed in of energy at medium and low voltage levels. Voltage control and balancing, stability and power quality issues, network protection are the important parts that have to be taken into account. (Chapman et al.,2008)

Subject of this thesis contains a study of harmonic analysis and a performance analysis between low-pass filter and wavelet de-noising algorithm. Power system

harmonics has a great deal of attention recently. Harmonic identification has an important role in industrial energy audit. Harmonics are primarily due to non-linear loads. Mainly it causes power system resonance so awareness of harmonic issues can help to increase plant power system reliability.

The aim of this thesis is to determine the harmonics and define which customer supply it to the system. All raw data's are recorded in the same cogeneration plant which consist 3 different customers. Timeline of the data is organized with respect to operating modes such as island mode, base load and low power mode and high power mode. Harmonic analysis is done by using wavelet ridge algorithm. Response of this algorithm shows frequency-amplitude based plot for identifying harmonics. After this analysis, a comparison is made by a FIR low-pass filter and de-noising algorithm. Low pass filter is designed by using MATLAB. For different cases filter is tested and results compared with de-noising response.

A detailed literature search will be given that including the studies are done recently. The details of the methods and selection of the mother wavelet will be explained in the thesis. Methods will be explained while obtaining filtering and de-noising process will be presented for eliminating harmonic components. Applications and result are also demonstrated with graphs and tables for frequency amplitude representations and daily data will be also shown. All results and graphical data's are presented and the work planned for the future will be discussed briefly.

Structure of the thesis consist 5 chapters. In chapter 2, combined heat and power, classifications, operating modes are represented. In chapter 3, methodology of the thesis which consist wavelet, Fourier analysis, filter theory and de-noising algorithm is presented. In chapter 4, application of harmonic analysis and harmonic filter design is presented and tested in raw data's. In chapter 5 conclusions, author recommendations for future work will explained. Finally, references, appendix and curriculum vitae are presented.

2   COMBINED HEAT AND POWER

Combined heat and power (CHP) or cogeneration is the simultaneous production of power and heat from a single fuel source. It is important that both products have a practical application area. The power product of CHP is electricity but the depending on the cogeneration technology heat product is used for indirectly producing steam, hot water or chilled water for process cooling. (Smit, 2006)

CHP technologies are more efficient than separate heat and power production. Efficiency calculation of electricity generation is determined by the relationship between net electricity and the fuel consumption. Heat rate is represented by consumed fuel per kWh of electricity generated. Total efficiency in CHP system is much higher than the separate generation. Figure 2.1 indicates the energy conservation on both separate generation and a cogeneration unit. A CHP system produces 85 units of useful energy through the conventional generation or separate heat and power systems use 134 units of energy, 64 for electricity production and 53 to produce heat. Overall efficiency is 63 percent. However, the CHP system needs only 100 units of energy to produce the 85 units of useful energy from a single fuel source, resulting in a total system efficiency of 85 percent.
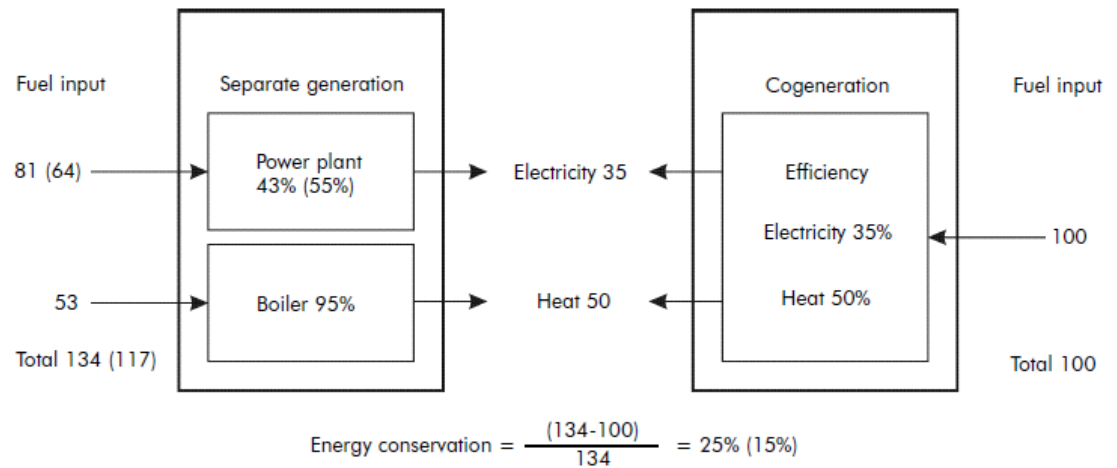
Figure 2.1 Comparison of energy conservation of cogeneration and separate generation of electricity and heat (Smit, 2006)

A system planner must consider several factors when building a cogeneration plant. The most important factor is the stable and predictable heat demand. Heat demand must always greater than the electricity demand. Cogeneration has high

initial cost relative to traditional power generation technologies. Energy market conditions and financial resources like prices, feed-in, tax reliefs must be stated and used in feasibility analysis. Proper place for installation is another factor because it requires significant amount of space in a plant.

2.1 Classification of Cogeneration Systems

CHP systems consist of number elements such as heat engine, generator, heat recovery and electrical interconnection. Primarily, classifications of these systems are implemented by using their prime movers. Prime mover technologies are listed in Table 2.1 with respect to power range, electrical and overall efficiencies are indicated (Knowles, 2011).

Table 2.1 CHP base technologies

CHP power generation technology	Power range (applied to CHP)	Power efficiency range (%)	CHP efficiency (peak) (%)
Steam turbine	500 kW – 100 MW	15 - 40	75
Gas turbine	2 MW – 500 MW	20 - 45	80
Combined cycle gas and steam turbine	20 MW – 600 MW	30 - 55	85
Reciprocating engine	5 kW – 10 MW	25 - 40	95
Micro turbine	30 kW – 250 kW	25-30	75
Fuel cell	5 kW – 1 MW	30-40	75
Stirling Engine	1 kW – 50 kW	10-25	80

The oldest prime mover technology is based on steam turbines. Steam turbines are mostly used where the demand for electricity is greater than one megawatt. Steam turbine cogeneration system has 2 types: backpressure or extraction/condensing. They replaced with reciprocating steam engines due to higher efficiencies and lower costs. The choices between these two turbines are related to power and heat quantity as well as economic factors. Gas turbine cogeneration systems can produce all electricity requirement of a site and energy released from the exhaust gases can be used by a heat recovery unit. Range of gas turbines varies from

2 MW to 500 MW and natural gas is the most common fuel used in combustion. These systems are highly efficient because of short start up time and flexibility in many operations. It has low heat to power ratio so that more heat can be recovered at higher temperatures. On the other hand if more power is needed in the site, it is possible to combine a gas turbine with a steam turbine to create a combined cycle. It can be seen in figure 2.2 in a combined cycle plant, fuel (natural gas) and air is mixed and ignited in the combustor. Then released gases blast through gas turbine blades and causing them to rotate. An alternator converts this mechanical energy into electrical energy. Produced electricity is transformed into high voltage by using transformers and sent to transmission network. Gas turbines also produce exhaust gases. Steam generated from the exhaust gases passed through a steam turbine to generate additional power. The exhaust or the extracted steam from the steam turbine provides thermal energy.
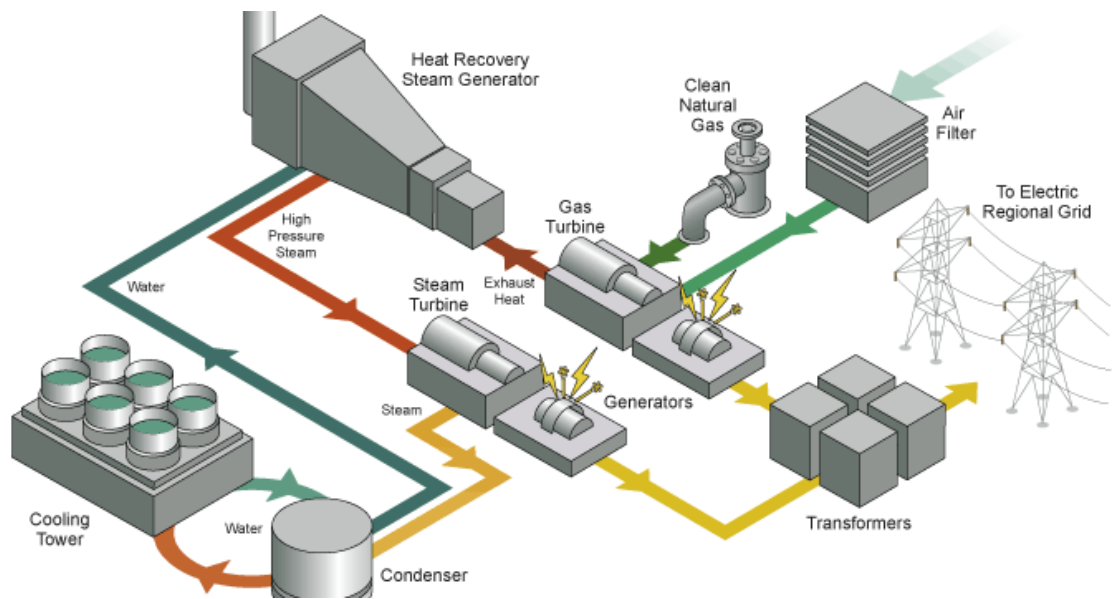
Figure 2.2 Combined cycle power plant

Micro-turbines are small, radial flow gas turbine. Reciprocating engine also known as internal combustion engines are used in cogeneration units. These units have high power generation capacity in comparison with the others. Heat is recovered from high temperature exhaust gas and engine jacket cooling water system. These systems are preferred when the electricity demand is higher than the thermal demand. (India Bureau of Energy Efficiency, 2004)

A cogeneration system can be also classified by the sequence of energy use. This basis divided into two groups as bottoming cycle and topping cycle. figure 2.3 depicted, in the bottoming cycle fuel produces thermal energy and waste heat is used to generate power through a recovery boiler and a turbine generator. Prime movers for bottoming cycle are organic Rankine cycle turbine and steam turbine.
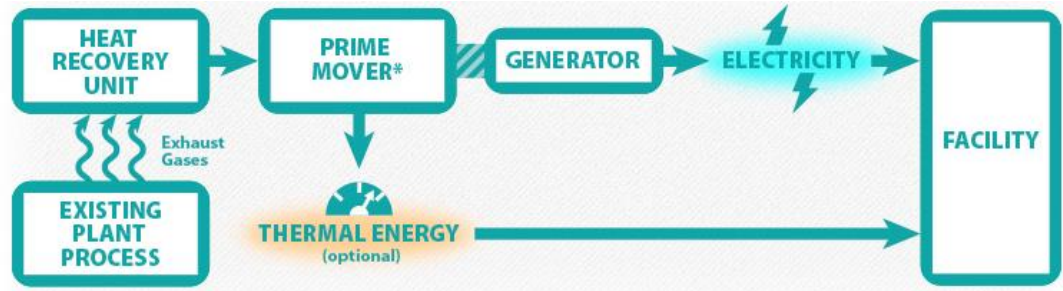
Figure 2.3 Diagram of bottoming cycle in CHP (Center for Sustainable Energy, 2015)

Figure 2.4 shows the working principle of topping cycle. In the topping cycle, fuel is initially used to produce power then thermal energy. Thermal energy is used to satisfy process heat or other thermal requirements. Prime movers for topping cycle are internal combustion engine, gas turbine, micro turbine, fuel cell technologies.
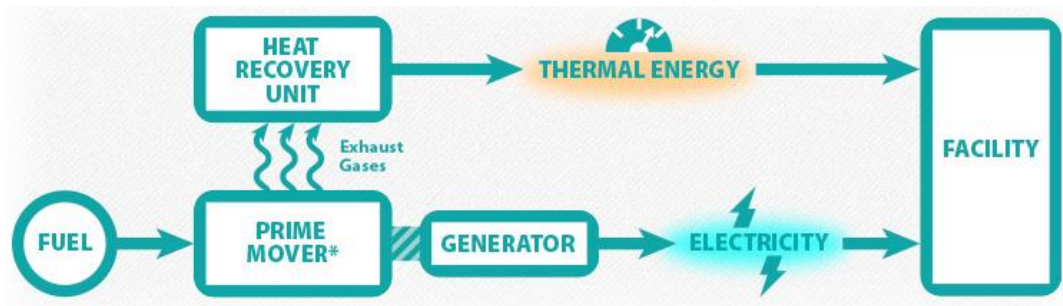
Figure 2.4 Diagram of topping cycle in CHP (Center for Sustainable Energy, 2015)

There are four different types of topping cycle for cogeneration systems. A gas turbine or diesel engine system with a heat recovery boiler creates a combined cycle topping system. Engine or turbine provides electrical/mechanical power and the boiler provides steam to drive a steam turbine. The second type burns any type of fuel and produce high pressure steam to produce electricity from steam turbine. Steam turbine is also produce low pressure steam to use in the process. This is called a steam turbine topping system. The third type operates heat recovery from engine exhaust and/or jacket cooling system. Product of this type converted into steam or hot

water. Lastly for the fourth type and the cogeneration unit which is used in this thesis; is a natural gas fueled gas turbine drives a generator. The exhaust gas goes to heat recovery boiler to make steam and process heat. (India Bureau of Energy Efficiency, 2004)

2.2   Operating Modes of Cogeneration

A cogeneration system can operate in many different modes. In parallel grid mode, cogeneration unit works continuously to ensure the electrical demand for the system. Rating of prime mover extends to full of its availability. Plants operating in parallel grid both import and export surplus power to the local distribution network. If electrical demand exceeds its limits, the unit only imports excess power from the grid. This is also called "base-load operation". A base-load system can also be sized by using thermal loads. If the system is inadequate for the demand supplemental power purchase may be required.

In case of limited capacity it is beneficial to import certain agreed amount of power from the grid and produce excess power with own power generating equipment. This is called "peak-shaving mode". Figure 2.5 shows the peak shaving operation that can be done by using an energy storage system. The storage system is charged at night (in red) when the system load is low, and then discharged during the day when the system load peaks. This helps reduce the customer's peak demand cost. (OpenEI, 2015)
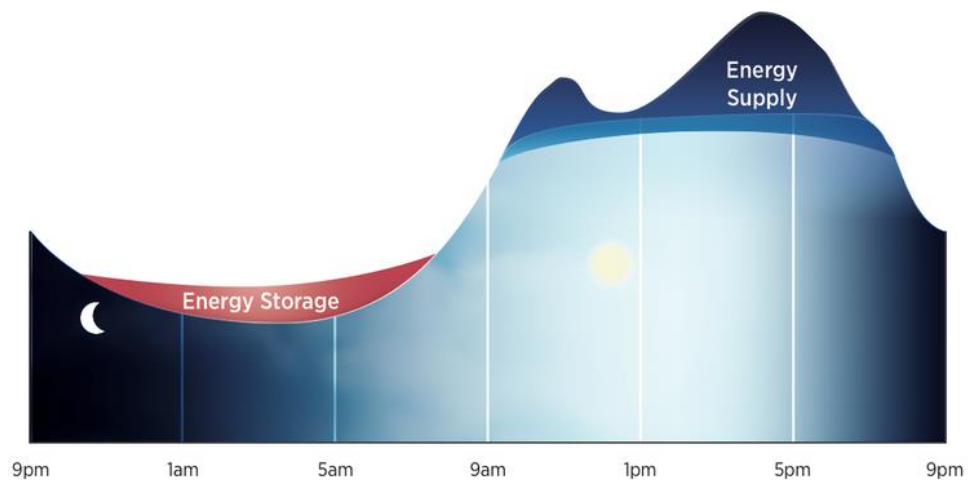
Figure 2.5 Peak shaving mode

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A cogeneration unit can operate independently from local electricity distribution network. This is called "island mode". The site is not connected with the utility; it may necessary to install redundant capacity to overcome unscheduled outages. This may be done by increasing the capacity or basically doing a load shedding. Load shedding can helps the system to be served at a certain capacity. Island mode operations can be seen on two forms. Stand-alone generators generate electricity when there is no connection between the plant and electricity grid. Also, if the plant is in parallel grid any failure in network lowers the generator to island mode.

Load tracking mode can be expressed in which the prime movers output is reduced when the site's energy requirements drop below the prime movers baseload output. Cogeneration system can be operating in load tracking if the engine output is supply the electrical requirements of the site. As in thermal tracking, prime mover is operated in a way so that no heat is rejected.

Final operating mode is economic dispatch mode where the system is operating during the hours when the cost of producing electricity is less than cost of purchased power. If a cogeneration system selling power to an electric utility it is recommended to operate in economic dispatch mode. (Zor ve Teke, 2013; OpenEI, 2015)

3   WAVELET ANALYSIS

As it seems a new method in signal processing, wavelet analysis dates back to the work of Joseph Fourier in the 19th century. Frequency based analysis have some limitations and the attention of researchers turned to scale based analysis. The first mention of wavelet is in 1909, in a thesis by Alfred Haar and many scientists made contributions in definition of wavelets, methods of wavelet transform and multiresolution framework.

"Joseph Fourier shows any periodic function can be expressed as an infinite sum of periodic exponential functions." Fourier transform (FT) tells whether a frequency component exist or not but it does not give any time information due to transforming into frequency domain. If the signal properties do not change in time which is called stationary signals, time information is not important. However, many of the signals are non-stationary or transitory characteristics. Fourier analysis is not suitable for detecting these important characteristics. (Polikar,2001)

Fourier transfrom is very sensitive to changes in the function. A small change can effect entire fourier coefficients. Location of frequency componenets are stored in phases and it is difficult to extract. If a function has Fourier coefficients all have the same magnitude, Fourier transform of this function is focused at a single point. Because of this, it is difficult to determine whether a signal includes a particular frequency at a certain point. (Lambers, 2008) Due to this limitations of FT a new technique is needed for non-stationary signal analysis so windowing technique is discovered by Dennis Gabor. This method provides a window function to analyze a small part of the signal at a time. This adaption is called Short time Fourier transform (STFT). It represents a signal with respect to time-frequency base. Main idea of STFT is to assume some portion of the non-stationary signal is stationary. If this area is too small, then we choose a narrow window to analyze the frequency components. Analyzed signal is divided into segments and multiplied with the window function "*w(t)*". For every multiplication STFT coefficients are calculated. Result of these calculations show frequency components for each time interval. It may be seen that STFT is suitable for frequency analysis; but there are some problems. Main drawbacks comes from the width of the window function. If we use a window with infinite length we get the frequency components but there is no time information just like Fourier transform. On the other hand, if we choose a narrow window we have a

good time resolution but poor frequency resoultion. All these obstacles lead to researchers for a scaled based analysis of "Wavelet". (Misiti et al.,2009)

3.1 Related Studies

In this part of the study, publications which used for the harmonic analysis, mother wavelet selection and de-noising techniques are examined. While examining publications, this study focused on wavelet based methods for all sections of the literature.

The advantages of using wavelet transform in harmonic analysis gives better resolution because of the scaled base. It provides distribution of energy with respect frequency sub-bands. A signal can be decomposed into uniform frequency bands and it can be easy to extract detailed information by using wavelet transform. Appropriate selection of sampling frequency spectral leakage is reduced. Meyer and Mallat's theorem (1989) says that given an orthogonal MRA we can find a function whose dilates and translates will create an orthonormal basis. (Pereyra, C.,2015) They develop the Multiresolution analysis (MRA) with using wavelets, which made it practical for engineering applications. MRA is wavelet based discrete filters used in signal processing. Ribeiro (1994) was the first to apply wavelet transform for analyzing nonstationary signals in power systems. The author presents the main concepts of the wavelet theory and application areas of distortion. Santoso et al. (1994) proposed an approach using wavelets to detect and localize electric power quality incidences based on time-scale domain. The authors proposed mother wavelet selection such as db4, db6 is chosen for the case of fast transients and db8 and db10 for the case of slow transients. Pham and Wong (1999) develop a novel approach based on wavelet transform. Proposed algorithm uses continuous wavelet transform to identify all frequency spectrum which includes harmonics and integer/non-integer sub-harmonics. Pham and Wong (2001) also present a method for eliminating the effect of imperfect frequency response of the filters in wavelet transform. Method recovers the signal magnitude by using wavelet based algorithm to give true harmonic amplitudes. Proposed method is used for the diagnosis of a motor-starting problem, which occurred in the Western Australia power system. Chen (2008) presented a multi-resolution wavelet method with 7 levels of reconstructing through db24 to decompose the harmonics. By experiment analysis on MATLAB, error is less than 1% which gives the tracking accuracy effectively. Gu et al. (2011) and Apetrei et

al. (2014) used discrete wavelet packet transform to decompose a waveform, and then based on wavelet coefficients harmonic contents are defined. All frequency contents with amplitudes and phases are calculated by continuous wavelet transform.

The choice of mother wavelet is a key parameter in wavelet transform. There are many case studies of choosing the best mother wavelet for harmonic analysis; but there is no agreement for the most suitable one. In the study of harmonic distortion in power system, Tse (2006) and Jing (2010) use 'Morlet wavelet' for estimation of the harmonics and inter-harmonics. Morsi and El-Hawary (2008) proposed a method on selection of mother wavelet which based on the energy of wavelet coefficients. Authors have found that the most suitable mother wavelet is 'Daubechies (db)' and the accuracy of the analysis increases with increasing wavelet order. For the high distortion level authors propose 'Coiflet wavelet' with low order gives accurate results. Kashyap and Singh (2008) made a statistical approach for finding suitable mother wavelet. They compare the performance of different mother wavelets on computation of the root mean square value by using DWT. Authors have found that the most suitable mother wavelet for analyzing harmonics is 'Daubechies with 7 coefficients (db7)'. Srivasta et al. (2009) made a case study on selection of mother wavelet for the power system harmonics using CWT. In their study, they compare the results with IEEE standard 1459-2000. Performance metrics for the analysis contains two methods: lowest root mean square error and minimum percentage error. It has found that 'Gaussian wavelet' is supported for the most suitable wavelet.

Wavelet de-noising removes the noise present in the original signal with optimal balancing and smoothing. It is not confused with smoothing process. Smoothing removes high frequency and retains low frequency components of the signal. DWT based de-noising process aims to remove low frequency contents of the signal. First application is done by Donoho and Johnstone (1995). Author proposed a method which based on thresholds DWT of the signal. Wavelet coefficients are reduced to zero if their values are below to zero. Lang and Guo (1996) also present a similar study for de-noising process. Wavelet threshold is used for de-noising power quality disturbances for classification. Giaouris et al. (2008) propose the use of wavelet transform to extract and identify specific frequency components. Authors presented a pseudo-adaptive de-noising method based on wavelets which adjust level of decomposition depending on the rotor speed. Wavelets are used for high frequency injection. Jie, (2009) detects and locates disturbing points based on soft and hard

threshold methods. On the basis author presented a new threshold function according to power quality signal characteristic. Proposed method is better for realization and de-noising effect. Joy et al. (2013) made a comparative study of different wavelet de-noising techniques. Discrete wavelet transform is done by using multiresolution analysis and digital filters. Through the analysis 'Daubechies wavelet with 4 coefficients (db4)' is used as mother wavelet. Authors have found that 'rigrsure' method gives the optimum performance. Performance metric is based on SNR and mean square error values. Gupta and Sharma (2015) create a power system model to generate voltage and current signals. White Gaussian noise is added in the input voltage to get a noisy signal. For the analysis wavelet packet tool is used and 'symentic family (sym)' is selected as the mother wavelet.

3.2   Definition of wavelet and wavelet families

"A wavelet is a waveform of effectively limited duration that has an average value of zero." (Arulmozhi and Nadarajan, 2003) Unlike a sine wave, wavelet has a limited time duration, asymmetric and irregular characteristic. Wavelet analysis is primarily explained as a windowing technique with variable-sized windows. Shannon's time domain representation is evolve and develepod as a scale based representation with the wavelet analysis. Evolution of this technique is demonstrate in figure 3.1
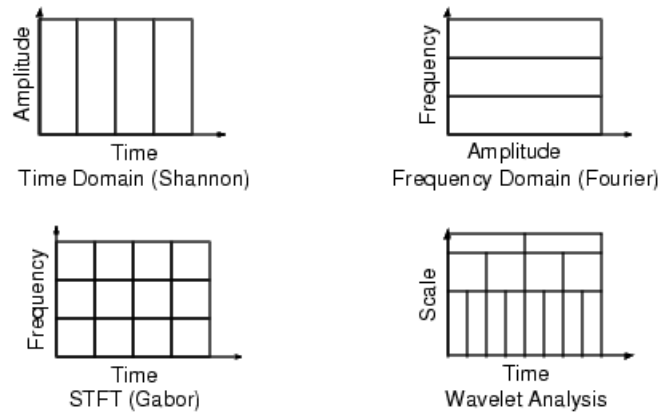
Figure 3.1 Evolution of wavelet analysis

Fourier analysis breaks up the signal into sine waves but wavelet analysis divide signal into shifted and scaled version of the original wavelet. This is called as

"mother wavelet". Wavelet analysis transforms time domain signals into time-frequency domain and estimates both domains instantaneously.

Primarily, wavelet analysis is the projection of a signal $x(t)$ to a space spanned with the scaled and translated replica of a mother wavelet and the wavelet coefficients are calculated as shown as

$$W_s(a, b; \psi) \triangleq \int_{-\infty}^{\infty} x(t)\, \psi_{a,b}^*(t)dt \qquad (3.1)$$

where a and b are the dilation and translation coefficients, respectively and

$$\psi_{a,b}(t) \triangleq \frac{1}{a}\psi\left(\frac{t-b}{a}\right) \qquad a \in R^+, b \in R \qquad (3.2)$$

where is the specific mother wavelet .

Mathematically, Fourier transform is the sum of the signal multiplied by a complex exponential. The result gives the fourier coefficients and applied on the signal to obtain sinusoidal components. Similarly, the CWT is defined as the sum over all time of the signal multiplied by scaled,shifted version of wavelet function

$$C(scale, position) = \int_{-\infty}^{\infty} x(t)\, \psi(scale, position)dt \qquad (3.3)$$

where C corresponds to coefficients calculated at any scale and position. This indicated the correlation or similarity between the signal and the scaled, translated wavelet.

There is a variety of wavelet families such as: Haar, Biorthogonal, Symlets, Daubechies, Coiflets, Morlet and discrete Meyer wavelets. Each wavelet family has its own unique properties that make them appropriate for a certain application. Generally, wavelet family or mother wavelet selection is characterized by many properties. For starters, numbers of vanishing moments are significant because wavelet analysis focus on the irregular parts. This is very useful when processing

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transient signals. Regularity is another key property that is useful when estimating the local parameters of a function. Support size means quantifying both time and frequency localization. Symmetry is also important when it comes to direction or emphasis in time. Lastly, presence of a scaling function is needed for analyzing low frequencies (Ngui et al.,2013).

3.3   Continuous Wavelet Transform (CWT)

Wavelet transform of a continuous time signal *x(t)* is shown as;

$$T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\, \psi^* \left(\frac{t-b}{a}\right) dt \qquad (3.4)$$

where $\frac{1}{\sqrt{a}}$ is the weighting function "*w(a)*". *w(a)* is set to for energy conservation which provides the wavelet at each scale to have the same energy. The asterisk indicates complex conjugate of wavelet function. Thus continuous wavelet transform in can be written as

$$CWT\{x(a,b)\} = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} \psi^*{}_{a,b}(t) dt \qquad (3.5)$$

Result of this convolution gives local maximas also referred as 'ridge'. Each local maxima consider an harmonic frequency and the peak values of the amplitude is the absolute value of the wavelet coefficient. For all local maxima represented in scalogram which shows the percentage of energy for each coefficient. (Srivastava et al., 2009)
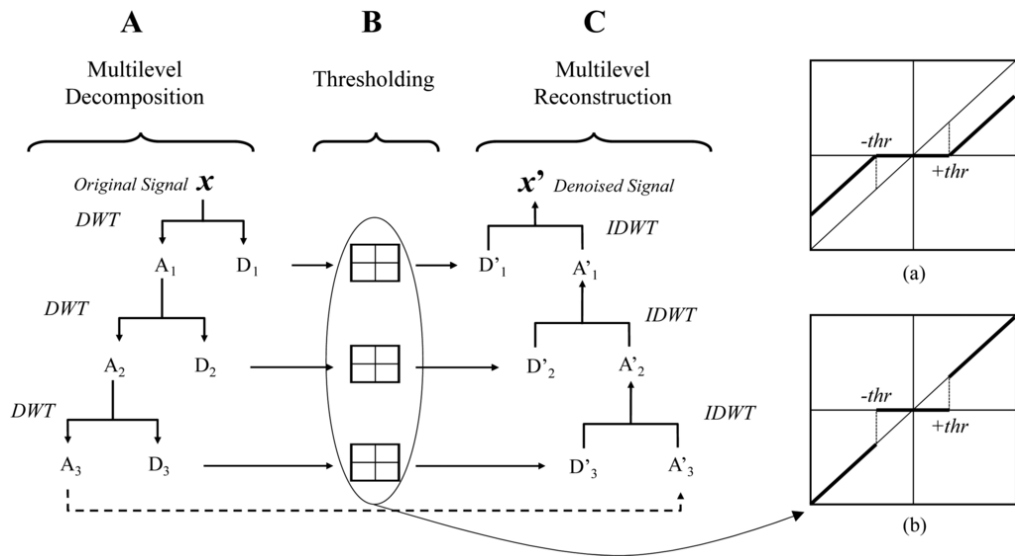
3.4   Wavelet Denoising

A signal is corrupted by many factors which effects as noise during transmission. This effect decrease the performance of the analysis. It is important to remove noise to get better processing. Denoising process can be describe as removing noise without compromising actual quality of the signal. Traditional

denoising method use lowpass or bandpass filters with cut off frequencies. However these techniques are incapable if the noise in the band of the signal to be analyzed.

It is difficult to model a noisy signal because of the non-stationary characteristics. An emprically recorded signal that is corrupted by noise can be represented as;

$$y(i) = x(i) + \sigma\varepsilon(i) \quad i = 0,1,2, \dots, n-1 \tag{3.6}$$

where $x(i)$ actual signal, $y(i)$ noisy signal and $\varepsilon(i)$ are independently normal random variables and σ is intensity of noise in $y(i)$. Usually noise characteristic is modelled as high frequency signal added to original signal. Traditional way to get rid of noise by using adequate filtering methods. This method is not suitable if there is an important information where the noise is located. The wavelet based denoising has provided many advantages in this part.

Figure 3.2 Schematic diagram wavelet de-noising: multilevel decomposition, thresholding, and multilevel reconstruction. Thresholding is obtained via (a) soft threshold or (b) hard threshold (Aymerich,2014)

As figure 3.4 stated there are three steps required for denoising a signal. These are decomposition, thresholding and reconstruction. Decomposition and reconstruction are done with the selection of appropriate mother wavelet. The idea of decomposition is implemented with an othogonal wavelet family. Signal is decomposed into sub signals corresponding to different frequencies. As in wavelet

transform signal decomposes into orthonormal wavelet functions. Reconstruction step is computed by using Discrete Wavelet Transform (DWT) of the signal. (Ergen,2012) The result of the DWT is a multilevel decomposition, in which the signal is decomposed in *'approximation'* and *'detail'* coefficients at each level (Mallat, 1989). This process is an equivalent of lowpass and highpass filtering. Discretization of the wavelet is computed as

$$\psi^*_{m,n}(t) = \frac{1}{\sqrt{a_0^m}} \psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right)$$ (3.7)

Using discrete wavelet wavelet transform of a continuous signal is written as

$$T_{m,n} = \int\limits_{-\infty}^{\infty} x(t) \frac{1}{a_0^{m/2}} \psi(a_0^{-m}t - nb_0)dt$$ (3.8)

Where $T_{m,n}$ are discrete wavelet transform of the continuous signal. Parameter m defined scale value, n is the location in the index. The values of $T_{m,n}$ are known as wavelet coefficients or detail coefficients. Scaling function has a form as the wavelet and it is expressed as:

$$\phi_{m,n}(t) = 2^{-m/2}\phi(2^{-m/2}t - n)$$ (3.9)

Where $\phi_{0,0}(t) = \phi(t)$is called as the father wavelet. Scaling function can be convolved with actual signal to produce approximation coefficients as:

$$S_{m,n} = \int\limits_{-\infty}^{\infty} x(t) \, \phi_{m,n}(t)dt$$ (3.10)

Actual signal is expresses as a combination approximation and detail coefficients by using combined series expansion as:

$$x(t) = \sum_{-\infty}^{\infty} S_{m_0,n} \, \phi_{m_0,n}(t) + \sum_{m=-\infty}^{m_0} \sum_{n=-\infty}^{\infty} T_{m,n} \, \psi_{m,n}(t)$$ (3.11)

Wavelet coefficients can be computed by using pyramid transfer algorithm. This refers to a FIR filter bank with highpass filter g, and lowpass filter h and downsampling by a factor 2 at each stage. (Mallat, 1989). Figure 3.5 and figure 3.6. shows the algorithm for pyramid transfer algorithm where DWT coefficients and approximations are presented. (Ergen, 2012) Wavelet filters h(n) and g(n) are constructed in equation (3.12) and (3.13) as follows:

$$h(n) = 2^{-1/2}\langle \phi(t), \phi(2t - n)\rangle \tag{3.12}$$

$$g(n) = 2^{-1/2}\langle \psi(t), \phi(2t - n)\rangle \tag{3.13}$$
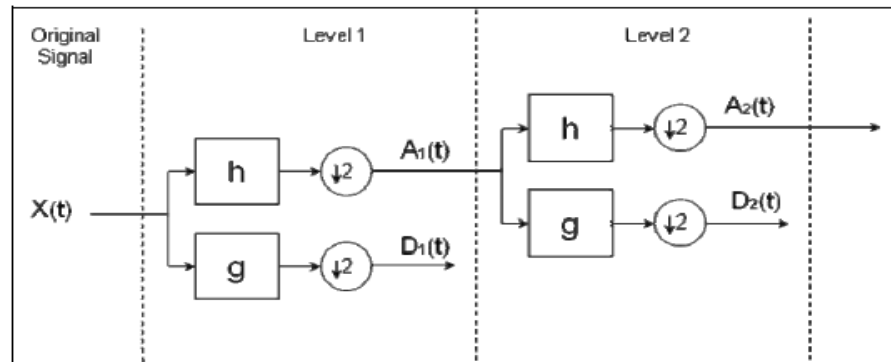
Figure 3.3 DWT decomposition for 1D signal
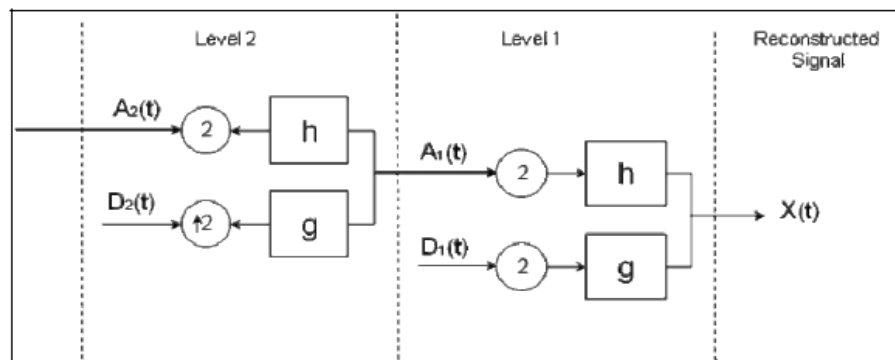
Figure 3.4 DWT reconstruction for 1D signal

Thresholding step is the selection of threshold level for denoising the signal. Since the work of Donoho and Johnstone (Donoho and Johnstone, 1994(a) ; Donoho and Johnstone, 1994(b); Donoho and Johnstone, 1995) there has been a lot of research on the way of defining threshold levels. Their approach suggest, thresholding can be applied soft or hard method, which also called as shrinkage. In

hard thresholding wavelet coefficients below a given value is setted to zero. In soft thresholding wavelet coefficients are reduced to the threshold value. A threshold value is the estimation of the signal noise level. It is generally calculated as the standart deviation of detail coefficient (Donoho and Johnstone. 1995). Hard and soft threshold are formulated in equation (3.14) and (3.15) which x is the input signal, y is the signal after threshold and λ is the threshold value;

$$Hard\ Threshold = \{y = x\ if\ |x| > \lambda\ or\ y = 0\ if\ |x| < \lambda\} \qquad (3.14)$$

$$Soft\ Threshold = \{y = sign(x)(|x| - \lambda)\} \qquad (3.15)$$
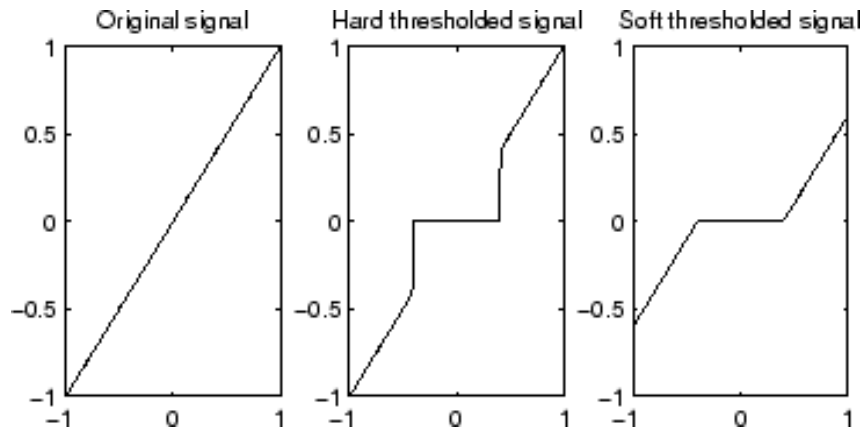
Figure 3.5 Visualization of hard and soft thresholding

Figure 3.7 shows the visualization of hard and soft threshold method. Hard threshold is a "keep or kill" procedure alternatively soft threshold, shrinks coefficients above the threshold in absolute value. Continuity of soft threshold has beneficial effect that shrinks false structures in the signal. (Joy et al,2013)

Finding the appropriate threshold value is important in de-noising process. There are four main methods for finding this threshold. These are; Universal threshold, Minimax threshold, Rigorous SURE threshold, Heursure method. Universal threshold is known as "sqtwolog" determines a fixed threshold value from soft threshold with Gaussian noise. It is formulated as $\lambda = \sigma\sqrt{2\log(n)}$ where the value of 'n' indicates the length of the signal and σ is the standard deviation. This estimation focuses on the data size not the context of the data. It provides a threshold

value larger than the other algorithms but output is smoother. Another de-noising algorithm is called minimax threshold method. It is derived from minimizing the risk involved in the signal. It is formulated as $\lambda = \sigma \lambda_n$ where λ_n is estimated to reduce the risk in the signal. Rigorous SURE threshold is not a global threshold technique that appropriate threshold is not applied on all of the wavelet coefficients. This method uses a threshold value λ_j at each level j of wavelet coefficients. Lastly, Heursure method is a combination of universal threshold and rigorous SURE threshold. It is useful when the majority of the coefficients are zero. If the set of coefficients is sparse, then the universal threshold is used; otherwise, SURE is applied. (Chourasia and Mittra 2009; Joy et al, 2013)

3.5   Mother wavelet selection

The purpose of wavelets analysis is to analyze non-stationary and transient signals such as power signal. However, when real wavelets are used, the transient characteristics are not resolved appropriately. Using complex wavelets, the magnitude and phase of wavelet coefficients can be separated. Therefore, the energy distribution of the signal can be analyzed by inspecting squared magnitude of the coefficients called as scalogram. In this thesis two different complex mother wavelets which are more suitable for power systems signals have been used for the harmonic analysis. These are "complex Shannon" and "complex Morlet". Real and imaginary parts of both mother wavelets are in figure 3.2. After the harmonic analysis "Daubechies" wavelet is used for the de-noising algorithm. Figure 3.3 shows the scaling function and wavelet description for the "db6"
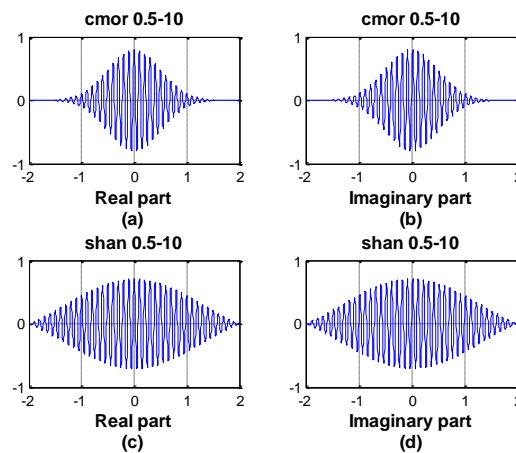

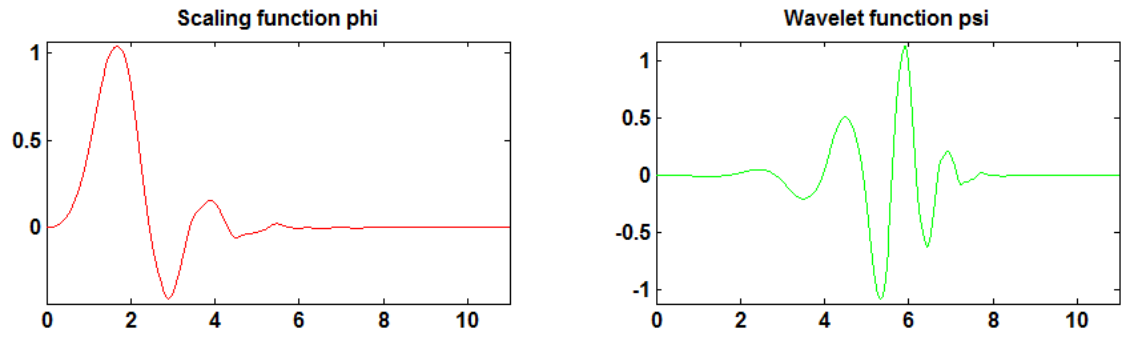**Figure 3.6 Description of "cmor0.5-10" and "shan0.5-10**

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Figure 3.7 Description of Daubechies wavelet with 6 coefficients "db6"

4 METHODOLOGY

4.1 Definition of the Plant

Gas turbine based cogeneration systems provides a stable supply of electrical power and can be isolated from the local distribution network. Figure 4 .1 shows that heat is produced either as hot water or as steam for use by the customers. If there is a need for cooling, the heat can be fed into absorption chiller providing a source of cold power. This can be used in air conditioning system. If the system provides electricity, heating and cooling these are called trigeneration plants. In our plant the system only provides electricity, steam and hot water so the unit is a cogeneration system.
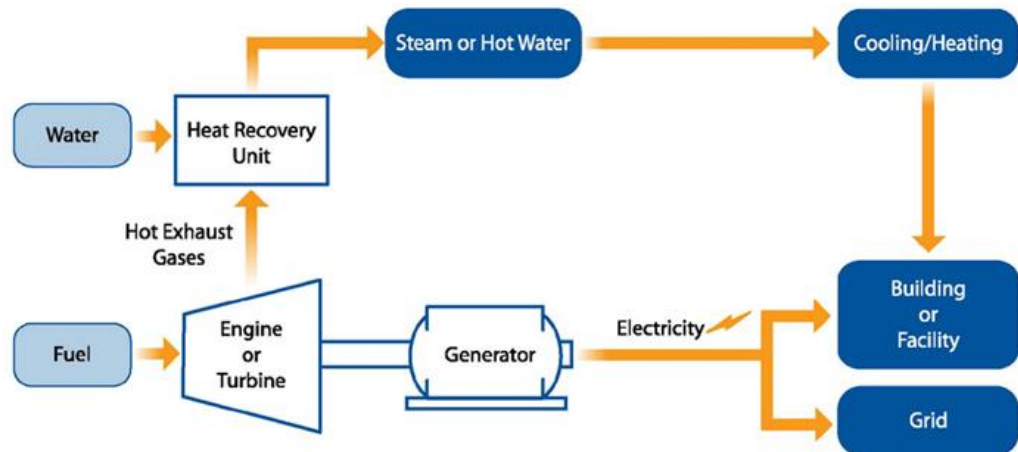

Figure 4.1 Gas turbine based cogeneration system

Given in Appedix A, İzmir has 46 distributed generation systems which 27 of them has a heat product. Our system has a 10 MW capacity and connected to the distribution network via 34.5 kV busbar. Cogeneration system includes 2 gas turbines (5 MW each), 3 different customers and a point common coupling (PCC) that connects the system to national grid. Single line diagram of the cogeneration system is given in Appendix B. Current and voltage specifications of these customers are presented in figure 4.2 and figure 4.3. All customers have similar voltage characteristics but due to different power rates current characteristics are different.
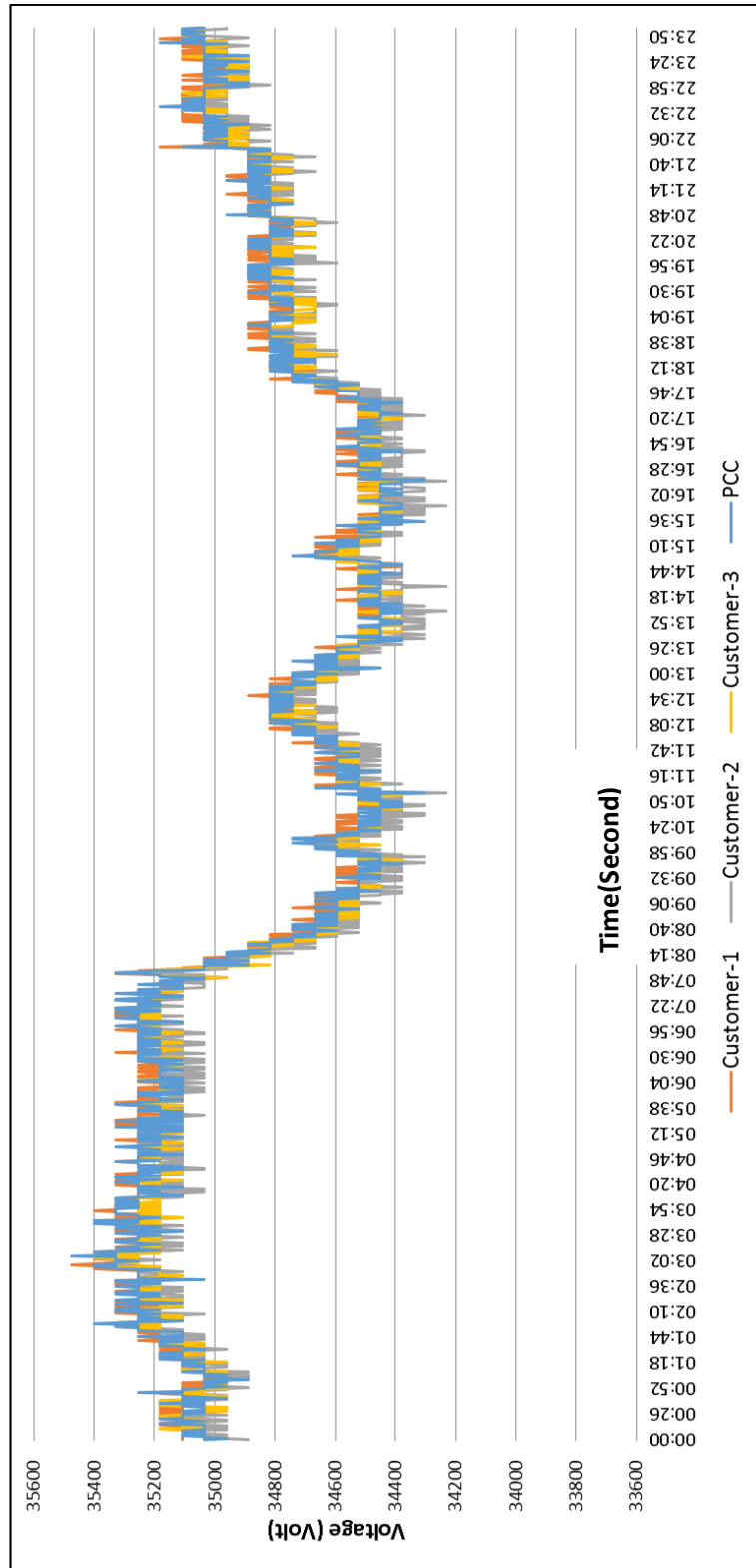
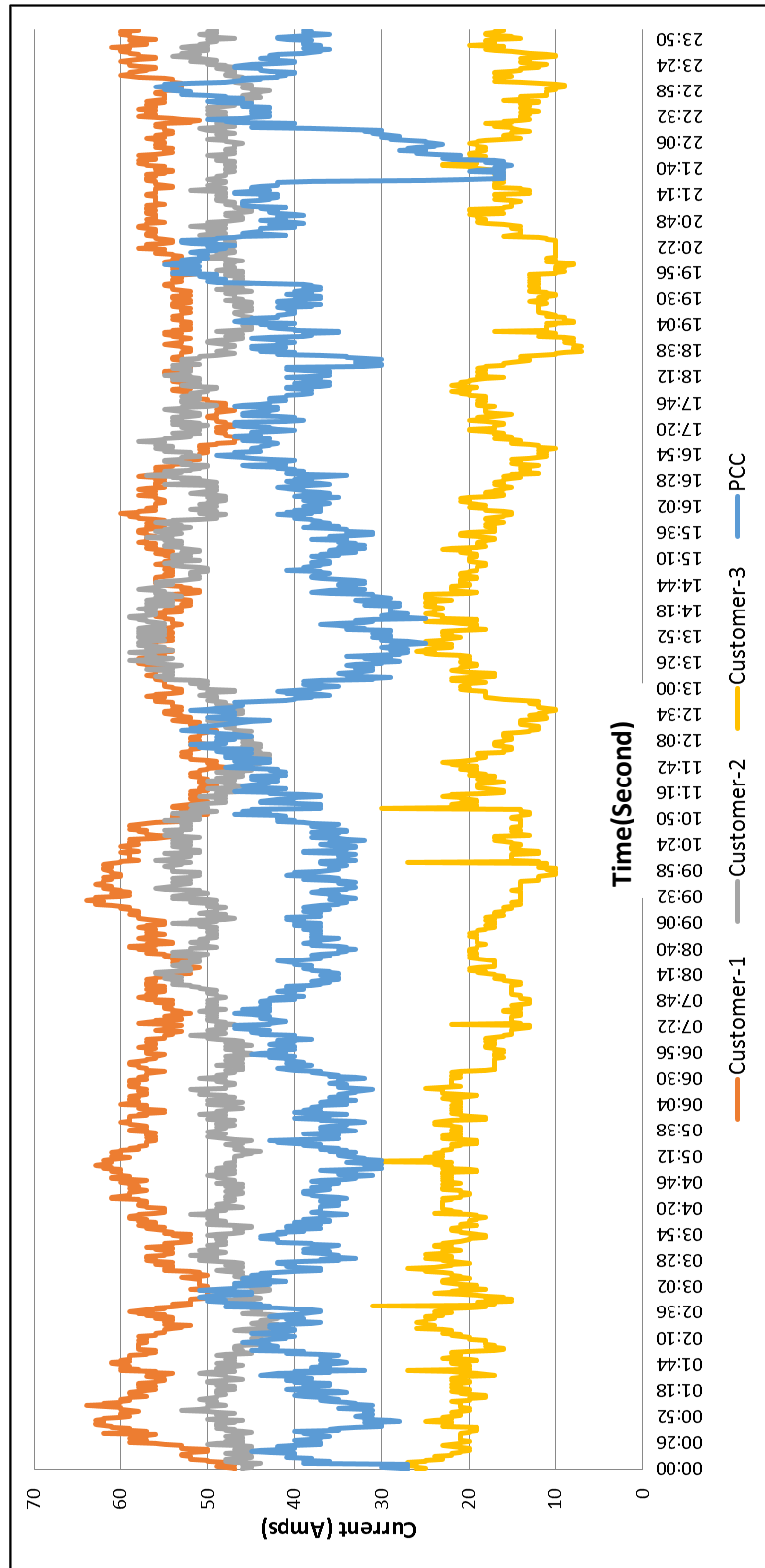**Figure 4.2 Voltage specifications for all customers**

Figure 4.3 Current specifications for all customers

4.2   Harmonic Analysis

Distributed generation design requires many analyses in order to reach optimal working conditions. First of all, power flow analysis must be applied to determine the parameters of the equipment. Short circuit analysis has to be executed in order to determine fault currents, which is necessary for the selecting circuit breakers. For an isolated cogeneration system, transient stability analysis must be done to ensure the stable operation in isochronous mode. (Hsu et al., 2011) Lastly, harmonic analysis is performed for the design of harmonic filters to solve distortion problems and power quality events.

In this thesis, "Fourier Transform" and "Wavelet transform" is used for determining harmonic frequencies in the system. Raw data used in the analysis is recorded in the field by system central computer as "DAT" format. It is recorded in several different operating modes such as island mode, high power mode, low power mode. In this thesis base load operation data is used as a raw data. Recorded signals have 678 data points which form 1 second.

Earlier analysis show that the frequency response of the signal is up to 350 Hz because of the 678 data points. Linear interpolation is used to approximate the value of the signal using two known values at other points. It is applied on the recorded data to enlarge signal to 1355 data points. In this way sampling frequency is made 700 Hz.

"Fast Fourier Transform" is by far the most popular method to analyze signals have multiple frequencies. It is a good way to determine frequency components in a stationary signal whose frequency does not change in time. But real life signals are not stationary and a planner must know in which times these frequency components exist. It has limitations that it only gives the frequency information of the signal; but it does not tell us when in time these frequency components exist. To overcome this problem "wavelet theory" is presented. It gives the time-frequency representation in addition to when frequency component exist in time. Wavelet analysis begins with choosing the right mother wavelet. Mother wavelet selection method is considered in chapter 4.2.1

4.2.1 **Mother Wavelet Selection**

Mother wavelet selection is one of the most compelling things when it comes to applying wavelet transform. Many applications depend on the choice of mother wavelet and the basis of selection is primarily trial and error. Several parameters have to be considered in choosing; such as similarity between the signal and mother wavelet, sampling rate and the duration of the signal and type of information to be extracted from signal. (Ngui et al., 2013)

In this thesis, raw data's and generated test signal are real valued signal. But it is preferred to select complex valued mother wavelets. Fourier transform of complex valued wavelet is zero for all negative frequencies. By using a complex wavelet we can separate phase and amplitude information of the signal. In this thesis, two different complex valued mother wavelets are used for the harmonic analysis. They are "complex Shannon (shan0.5-10)" and "complex Morlet (cmor0.5-10)". Both wavelets are selected by proper bandwidth and center frequency parameters. It is also known that they are suitable for continuous wavelet transform. A test signal is generated in order to test the proper mother wavelet. Test signal is formed as;

$$x(t) = \sin(2\pi 50t) + 0.33\sin(2\pi 150t) + 0.20\sin(2\pi 250t) + 0.14\sin(2\pi 350t)$$

First mother wavelet is complex Shannon "shan0.5-10". Center frequency of selected mother wavelet is 2.9750 Hz. Figure 4.4 indicates all fundamental harmonic and 3 other harmonics in the scalogram; but there are multiple extra frequency components between 0 to 50 Hz. In addition, continuous wavelet coefficients are not computed correctly so that complex Shannon wavelet is not suitable for power system harmonic analysis. Second mother wavelet is complex Morlet "cmor0.5-10". Center frequency is calculated as 5.9375 Hz. This wavelet has a complex sinusoid with a Gaussian envelope. Complex part shows the real and imaginary parts. Scaled and dilated cmor wavelet is applied on the test signal in figure 4.5. Results show that all frequency components and amplitudes are calculated correctly. Complex Morlet wavelet is the optimal mother wavelet for this application.
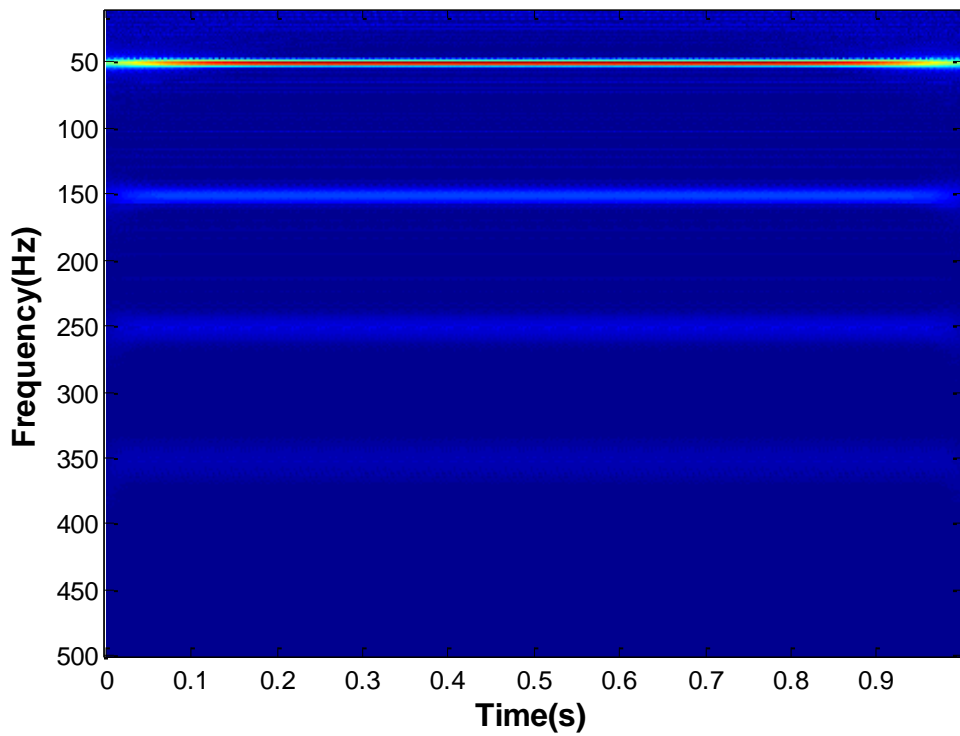
Mother wavelet: shan0.5-10
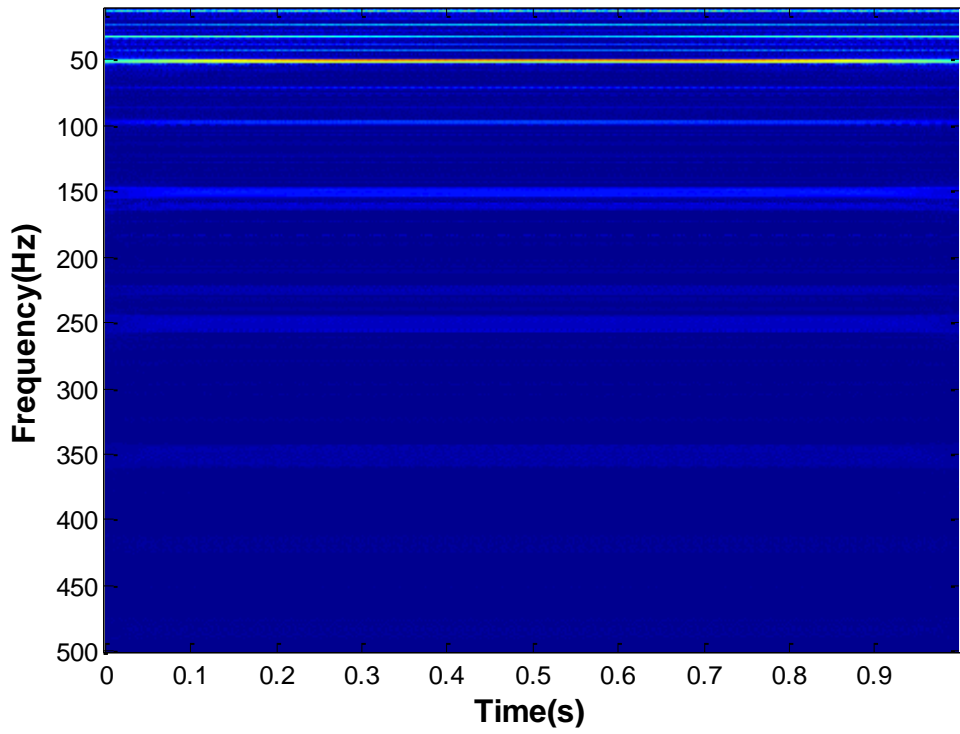
Figure 4.4 Complex Shannon wavelet analysis

Mother wavelet: cmor0.5-10

Figure 4.5 Complex Gaussian wavelet analysis

4.2.2 Harmonic Analysis on Raw data

In a cogeneration unit, on-site generator will track the grid voltage in acceptable limits. If this situation fails, the link between grid and on-site generator will be broken. This can be caused by power quality events or huge load variations. Any disturbance will affect entire system. Voltage dips, sags, swells and interruptions effect many microprocessor based equipment. In addition to these power quality events, harmonic components can also appear in the system. Electrical motors, UPS devices, adjustable speed drives etc. are harmonic sources. These harmonic sources can cause over heating by excessive currents, overloading capacitor banks which is used for power factor correction, power line disturbance problems with electronic and computer control systems and telephone interference. In this thesis, harmonic analysis is done by 2 different algorithms. Fast Fourier algorithm gives a frequency response of the signal with respect to their amplitudes. Wavelet algorithm gives the time-frequency spectrum of the signal. All raw data's used in this study are logged by using data logger in center computer. Diagram of the plant is demonstrated in figure 4.6
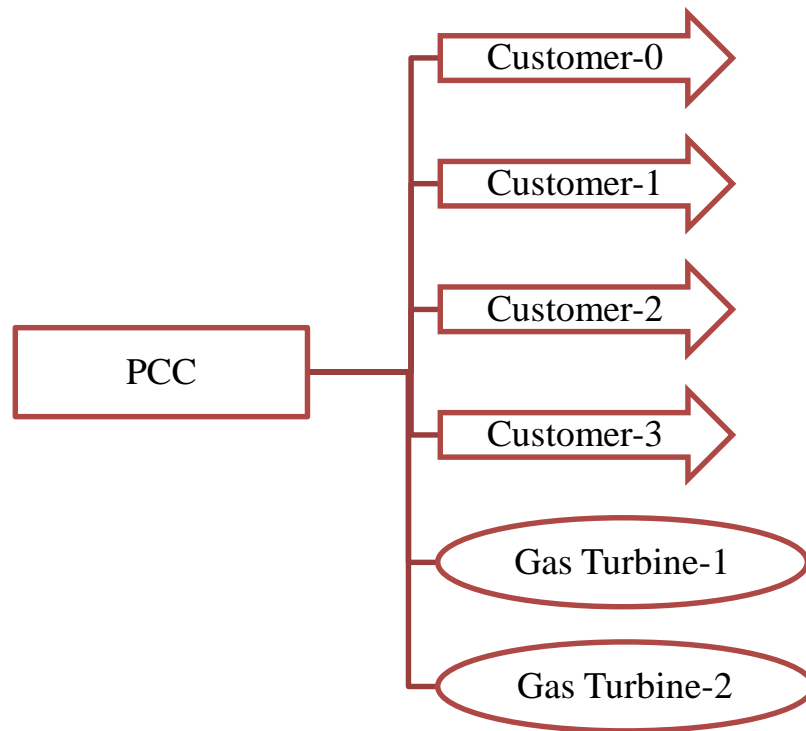

Figure 4.6 Diagram of the cogeneration plant

Customer-0 indicates the facility that consist the cogeneration unit. Customer 1 is a beverage facility that has an installed power of 9 MVA. It has 12 compressor units which located in cooling and compressed air. They do not need to perform any harmonic measurement because they don't encounter any harmonic related incident. Customer-0 center computer logged three phase voltage and current raw data's from the distribution network. Figure 4.7(a) indicates three phase current drawn from the customer-1. Phase A is chosen for the harmonic analysis which can be seen on figure 4.7 (b)
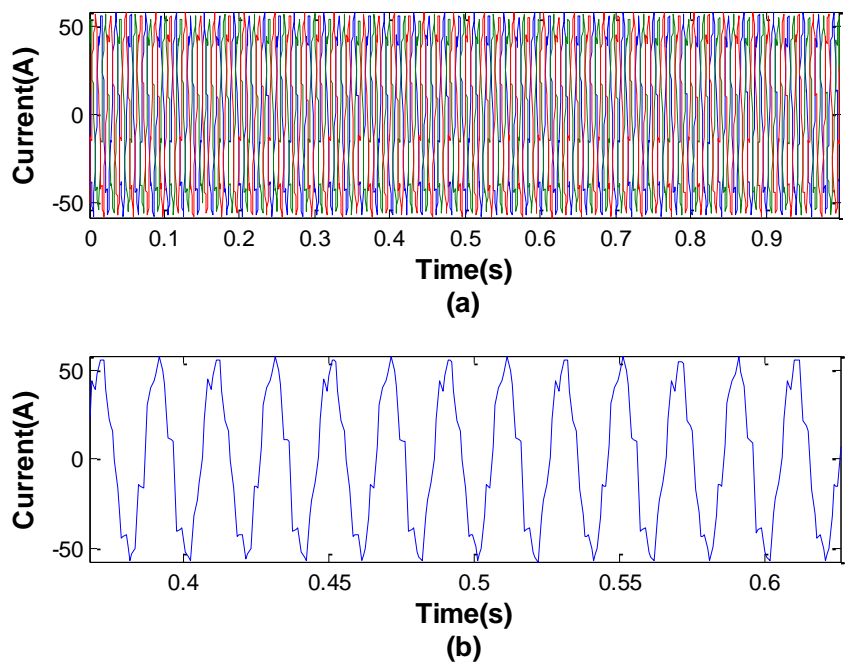
Figure 4.7 Customer-1 current

In figure 4.8 (a), Fourier spectrum of customer-1 shows there is a 5th and 7th harmonic distortion in the system. There are multiple inter harmonic components located in 326.6 Hz and 426.7 Hz. Due to limitations of Fourier spectrum it is only seen where the frequency components located. Later; chosen mother wavelet "cmor 0.5-10" is scaled and applied to the system. Scalogram in figure 4.8 proves that there is a 5th and 7th harmonic distortion in the system. Wavelet coefficients are gathered on specific harmonic frequencies. Darkest color on the scalogram shows the highest amplitude of the frequency. It is also seen there is an instantaneous change in amplitude during 0.15 seconds.

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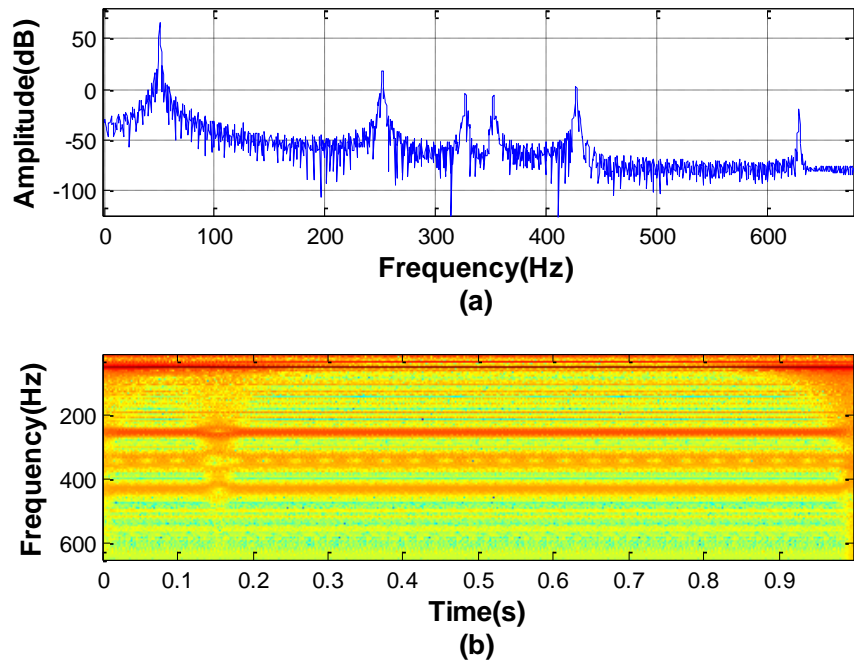
Figure 4.8 Fourier spectrum and Scalogram of customer-1 (a) Fourier Spectrum (b) Scalogram

Customer-2 is a factory in food industry which has a total capacity of 8 MVA. It supply electric and steam from the cogeneration unit. It has 9 electric motors over 100 kW which has a speed between 1400-2800 rpm. These motors are used in cooling, air conditioning and in homogenizer units. Customer-2 made a harmonic measurement back in 2010. Current and voltage harmonic values come up under the standard limits. But there are harmonic filters in the low distribution side. Figure 4.9 shows current waveform of customer-2. Customer-2 has drawn approximately 54 A. Current is nearly sine waveform. Harmonic components are too small so that can be neglected.

Customer 3 is a factory in animal feed sector. It draws less current than the other customers. Figure 4.11 (a) shows the three phase current of the customer-3. Phase A is chosen for the harmonic analysis which can be seen on figure 4.11 (b). Harmonic analysis on figure 4.12 shows there are multiple harmonic components in the spectrum. Inter-harmonics can be seen in the scalogram. Deeper analysis must be done in order to find the source of the harmonics.
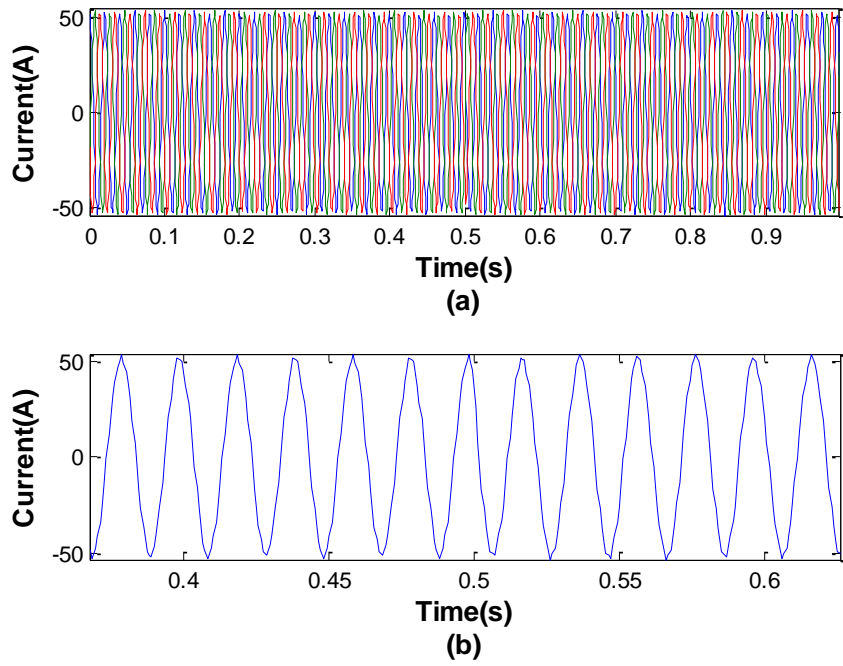
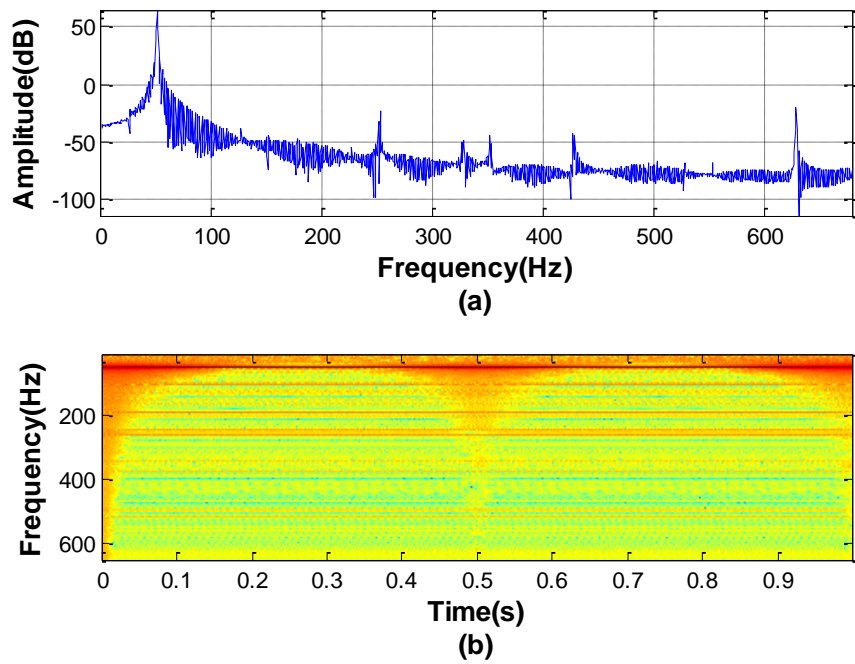**Figure 4.9 Customer-2 current**
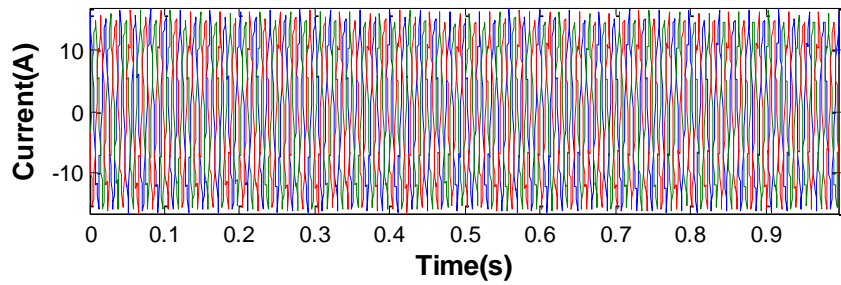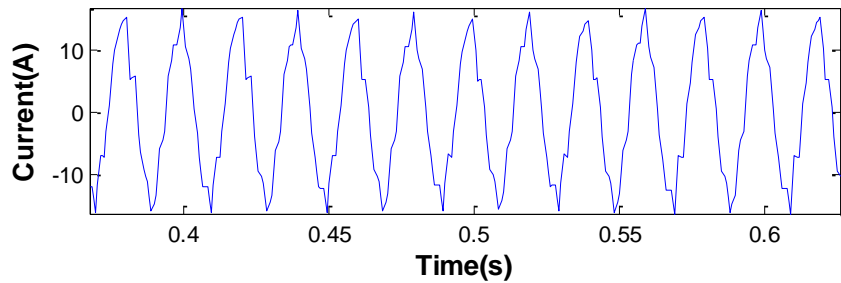

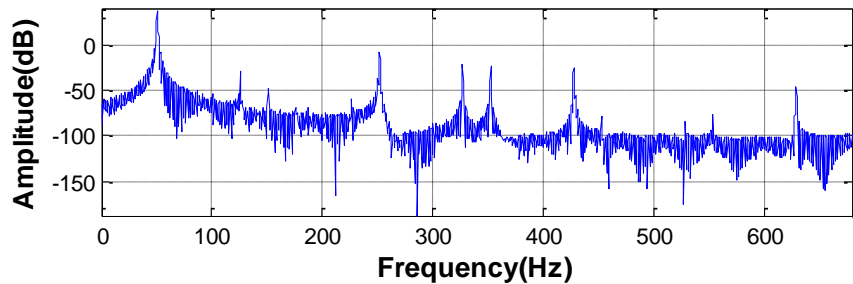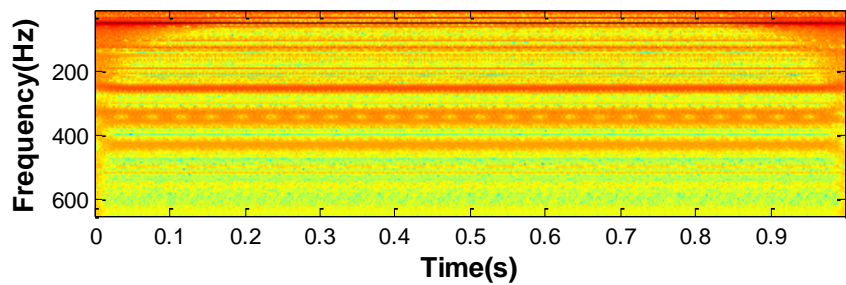**Figure 4.10 Fourier spectrum and Scalogram of customer-2 (a) Fourier Spectrum (b) Scalogram**

Figure 4.11 Customer-3 current (baseload)

Figure 4.12 Fourier spectrum and Scalogram of customer-2 (a) Fourier Spectrum (b) Scalogram

4.3   Filtering and de-noising

A low-pass filter allows the signals below cutoff frequency and attenuates signals above the cutoff frequency. Filters are designed by defining their passband and stopband. By removing higher frequencies filter creates a smoothing effect. When a filter applied to a signal it produces slow changes in the output values. In this case it is easier to see any change in the signal-to-noise ratio with minimal signal degradation. Low-pass filters like moving average filter or Savitzky-Golay filter are often used to remove noise, data averaging and discover important patterns. (Mathworks, 2015)

MATLAB signal processing toolbox has a filter visualization tool named as "fdatool". Figure 4.13 shows the basic concepts of this analysis tool. In this thesis a low pass filter is designed to mitigate harmonics. Filter coefficients exported and saved in MATLAB workspace. After that it is performed a convolution between raw data and filter coefficients to get the filtered output.
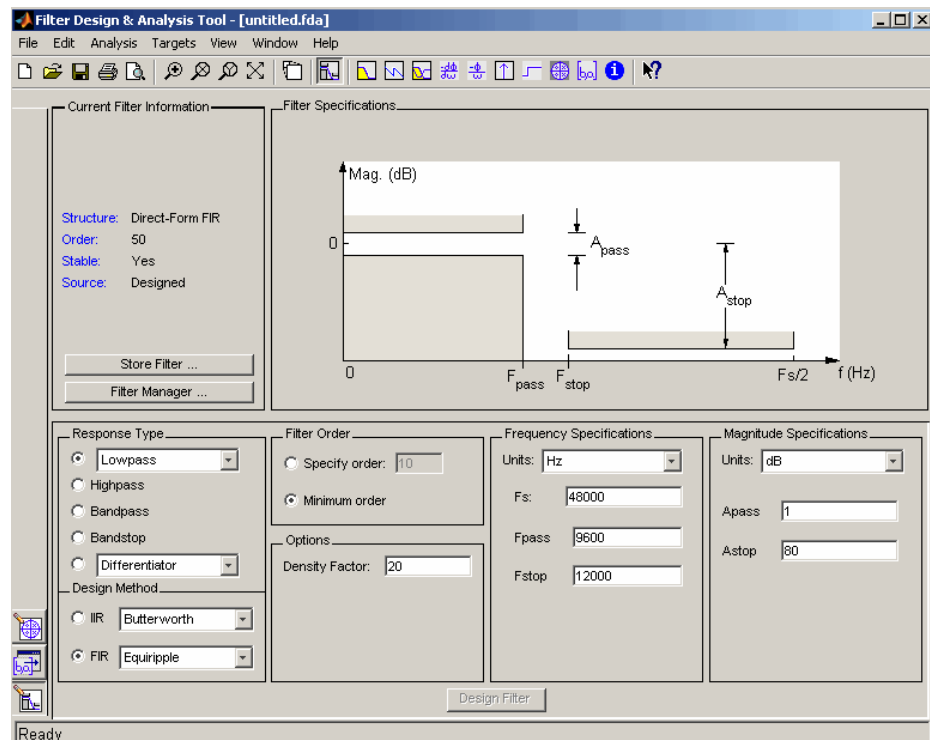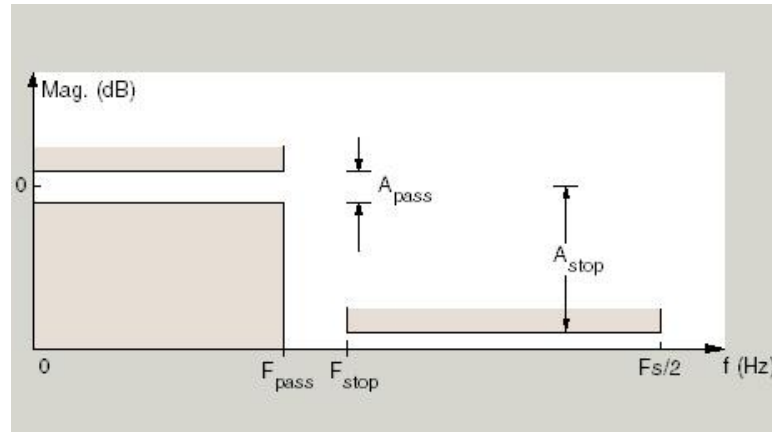

Figure 4.13 MATLAB filter design and analysis tool

Figure 4.14 Low-pass filter specification

Designed low pass filter has a finite impulse response (FIR). FIR filters are designed by finding filter coefficients and filter order that meat a certain specification. Fdatool gives the knowledge of filters impulse response. This allows a process called convolution in time domain. Visualization of filter specifications is shown in figure 4.14.

Table 4.1 Lowpass FIR filter specifications

Passband frequency	Passband ripple	Sampling frequency	Filter order	Stopband frequency	Stopband Ripple
75 Hz	0.5 dB	1356.9 Hz	12	190 Hz	20 dB

After all the parameters are entered in fdatool, filter coefficients are computed. Designed filter is a direct-form FIR filter which is order of 12. Filter coefficients are exported in MATLAB workspace in order to load in convolution process. Magnitude response is shown in figure 4.15. As it can be seen in the figure, after the convolution it is desired to reduce the harmonics 20 dB.
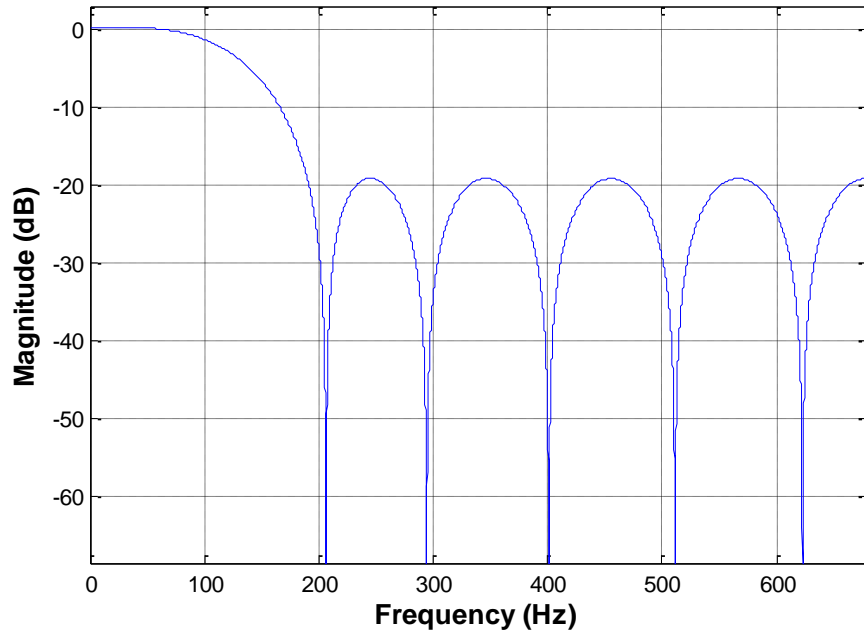
Figure 4.15 Magnitude response of low-pass filter

The main study of this thesis is based on harmonic filtering by using wavelet de-noising algorithm. Main challenge of using de-noising algorithm is to define the proper threshold value. Finding the most convenient threshold value is extended to Donoho and Johnstone work.(Donoho and Johnstone,1994(b)). Joy et al., 2013 states "Motivation to thresholding is based on the assumptions that the decorrelating property of a wavelet transform creates a sparse signal: most untouched coefficients are zero or close to zero. There must be a balance in choosing appropriate threshold value. A very large threshold cuts too many coefficients, resulting in an over smoothing. Conversely, a too small threshold value allows many coefficients to be included in reconstruction, giving a wiggly, under smoothed estimate." (Joy et al. 2013). Generally; threshold choosing methods are divided into global thresholding and level-dependent thresholding. Global method is applied to all wavelet coefficients but as the name implies level-dependent method is changed for each wavelet level.

In this thesis, it is used two different functions to calculate threshold value and application of de-noising. 'ddencmp' returned default values for de-noising or compression, using either a wavelet or wavelet packet. Result of this function gives a fixed threshold value by using "Universal threshold" formula and the choice of soft or hard threshold. On the other hand 'wdencmp' function performs a de-noising or

compression of a signal using wavelet. First of all signal is decomposed its detail wavelet coefficients. After that, soft thresholding is applied. Lastly, signal is reconstructed with using original approximation coefficients and modified detail coefficients.

In the following; harmonics which have found in earlier chapters are filtered and de-noised. A level 2 wavelet Daubechies 'db 6' is chosen for the comparison with designed FIR filter. Characteristic of a FIR filter creates a group delay. Group delay of a linear phase FIR filter is constant for all frequencies because impulse response is symmetrical. Linear phase can be defined as that all frequencies input signal experience the same delay. It can be calculated as (N-1)/2 samples for N is the filter length. Choice of level of decomposition is also important in wavelet analysis. In the low frequency region delay can cause small phase shift; but in a noisy region peak values can change. On the high frequency region, phase shift can cause instability.

Customer-1 and customer-3 are used as a raw data for the performance analysis of filter and de-noise algorithm. Threshold value is calculated for each customer. Filter response for customer-1 is shown in figure 4.16 (a). Harmonics are reduced 20 dB in figure .16 (b). There is a group delay which caused by the filter characteristic. De-noise algorithm is applied on the customer-1 data in figure 4.17. Calculated threshold for customer-1 is 27.9950. Root mean square error between original and de-noised signal is 0.1606. Filter response for customer-3 is shown in figure 4.18. Calculated threshold for customer-3 is 9.4912. De-noising algorithm response is shown in figure 4.19. Root mean square error between original and de-noised signal is 0.0350. For both of the customers there is no phase shift and harmonics are reduced very well.

As it can be seen in the figures, de-noising algorithm response is better than the FIR filter scheme. In real time applications data alignment is a serious problem. For basic current de-noising, simple FIR filters are better to use because it is implemented simple and low-cost hardware or with some additions to a software. But in the cases where there is need to be extracted useful information like adjustable speed drives, motor stator etc. wavelets should be preferred.
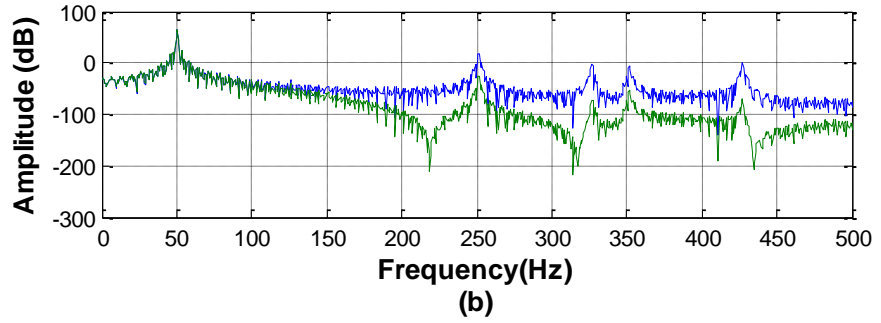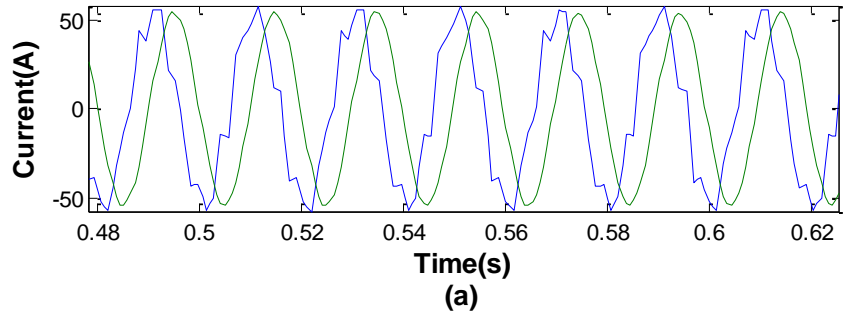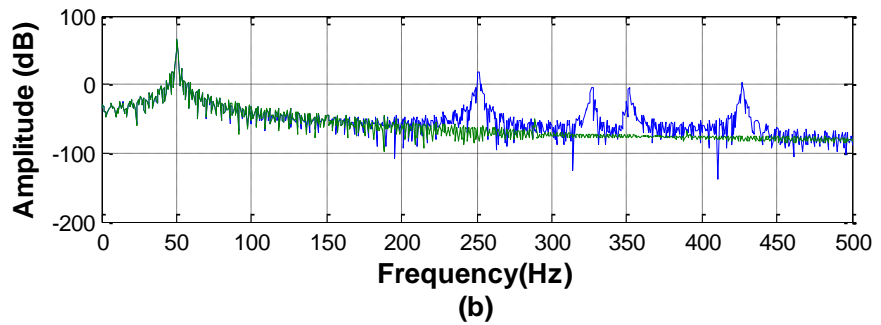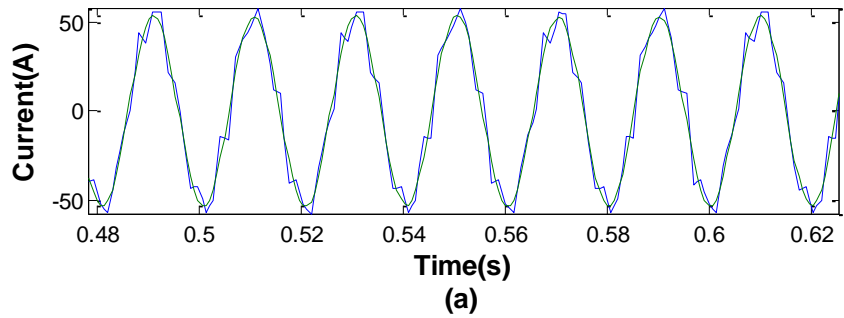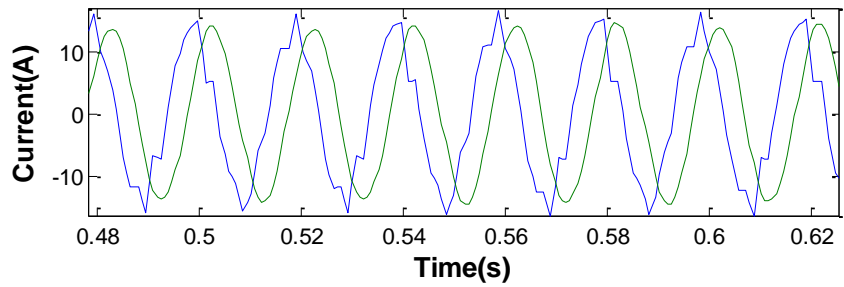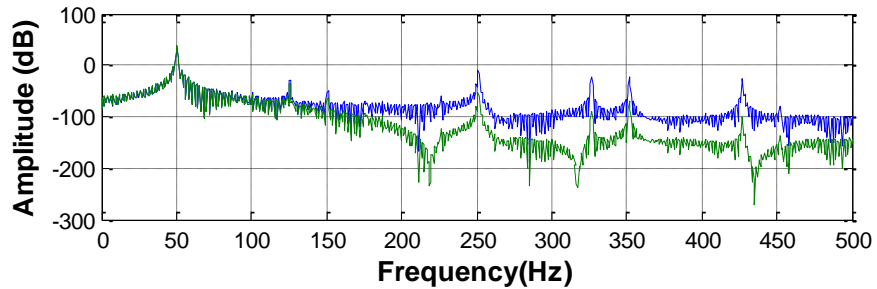
Figure 4.16 Customer-1 filtered harmonics

Figure 4.17 Customer-1 de-noised harmonics

35
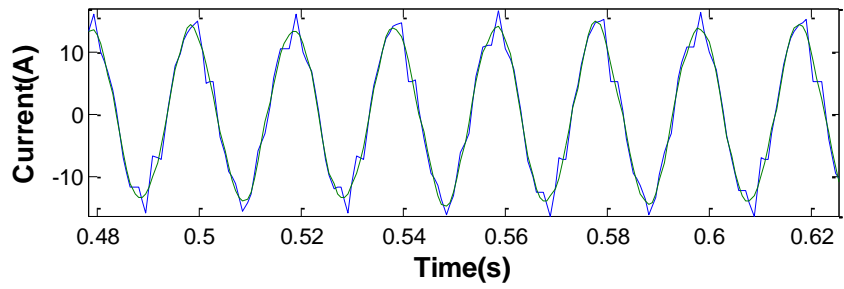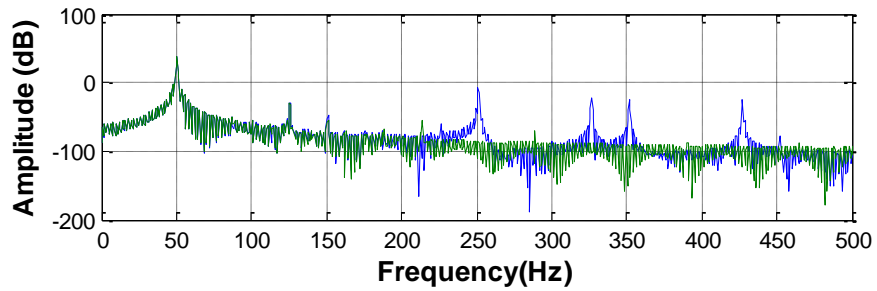
Figure 4.18 Customer-3 filtered harmonics

Figure 4.19 Customer-3 de-noised harmonics

Gas engine cogeneration systems can be act as a captive power plant in island mode. Captive power plant is a form of distributed generation providing a localized source of power. These sources can be electrical or heat. The plants can be operated in grid parallel mode to export surplus power to electricity distribution network or basically operate in island mode. Island mode operation can be form as when stand-alone generators are not connected to grid or independent production from the grid in a power supply failure.

When an outage occurs in local supply, unit is change from parallel to island mode instantaneously. If this situation happens, CHP plant continues to supply site loads without interruption; on condition that the site load immediately limited to the output level of the CHP plant. This is achieved as load shedding, which can automatically disconnect the selected parts of the site loads. If this load limitation does not happen, CHP plant shut down when there is a disturbance in the local area electrical system.(Flin, 2010)

According to analysis in earlier parts of the thesis, all customers have different amounts of harmonic components. In comparison with the island mode against baseload conditions, it is conducted an analysis in island mode operation conditions. Baseload current characteristics of customer-1 and customer-3 showed in figures 4.20(a) and 4.21(a). Island mode current characteristics of customer-1 and customer-3 are shown in figures 4.20 (c) and 4.21 (c). Scalograms of these waveforms are shown in figures 4.20(b), 4.20(d), 4.21(b), 4.20(d). In island mode operation, current waveform is much smoother than the baseload operation. In baseload, the cogeneration unit is working in parallel with grid so a current is drawn from PCC. Harmonic components from the utility grid can flow through PCC and affects the whole system. In order to eliminate harmonics, harmonic filters can be set up.
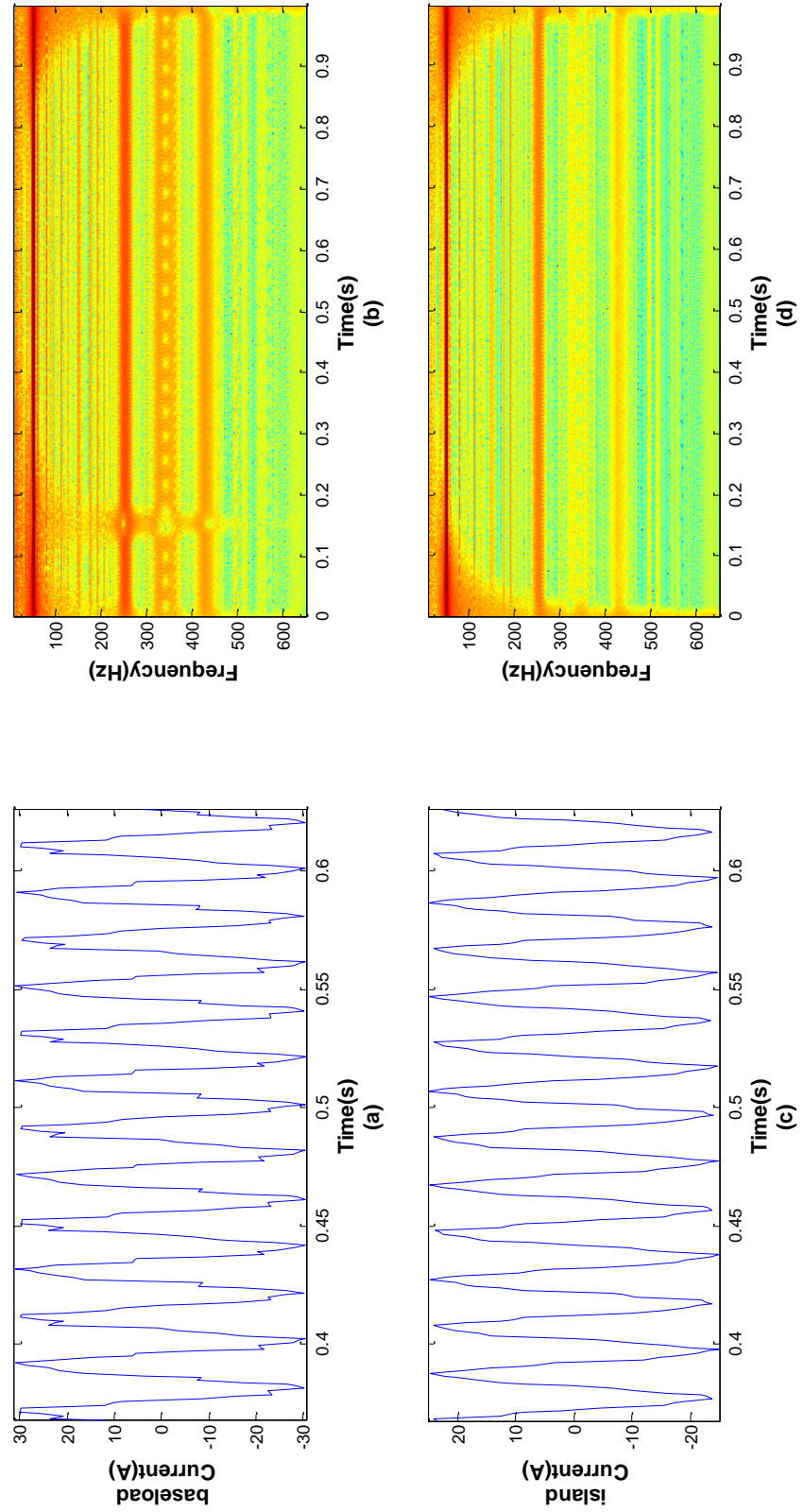
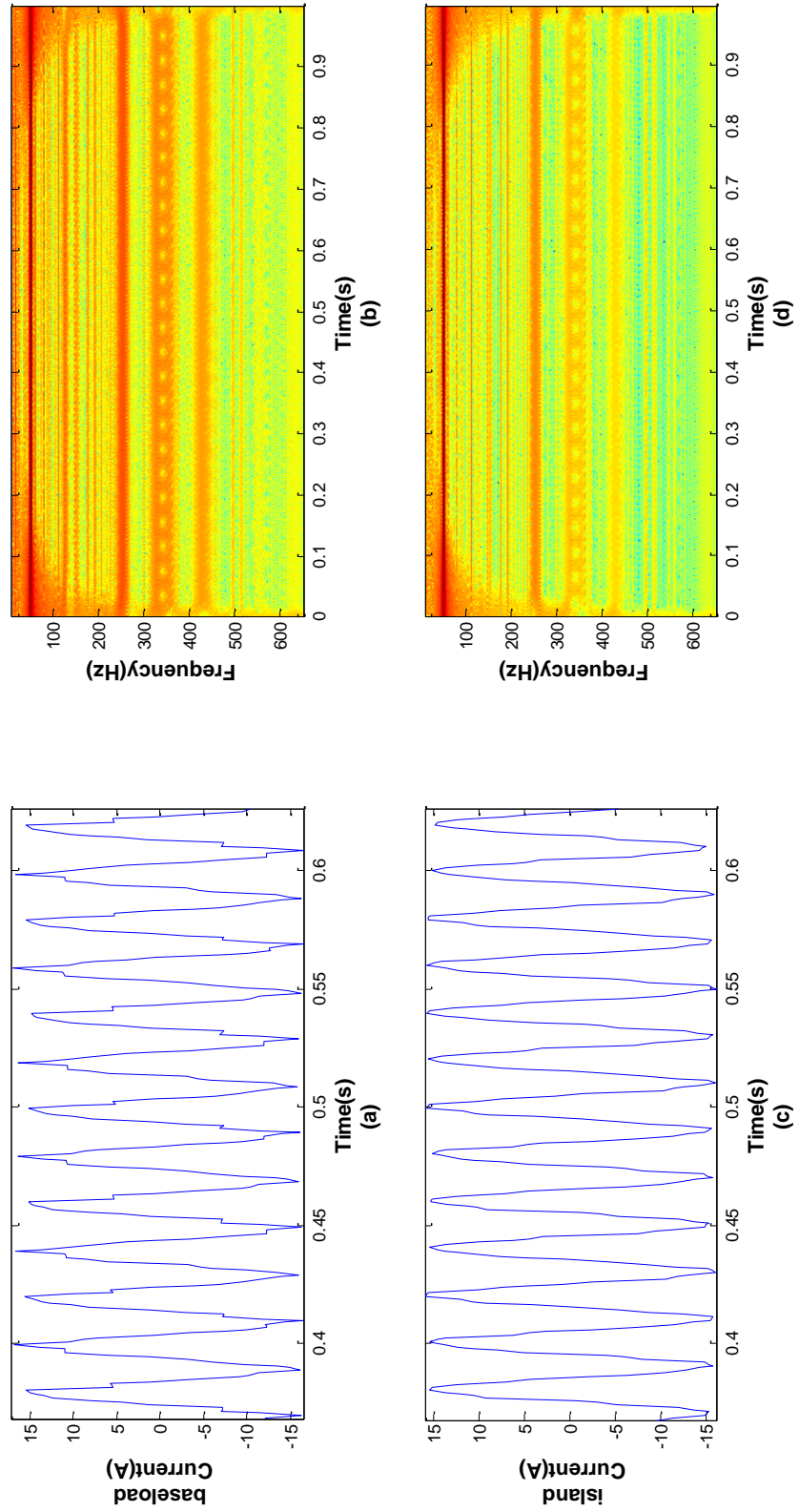**Figure 4.20 Comparison of harmonic analysis in customer-1**

Figure 4.21 Comparison of harmonic analysis in customer-3

5 CONCLUSION

In this thesis, a wavelet based harmonic analysis is presented for a plant with a cogeneration unit. It is empirically demonstrated that there is a harmonic distortion on the loads and PCC of the system. A set of logged data's are used in the validation process with using MATLAB. This thesis also covers the related studies that have been done in wavelet based methods. Harmonic analysis, mother wavelet selection for harmonic analysis and de-noising with global thresholding are analyzed.

With the guidance of the prior work, de-noising algorithm is applied on the logged data's to eliminate harmonic distortion. It has been seen that de-noising with universal threshold can eliminate harmonics effectively against traditional low-pass filtering. Phase shift of the actual signal is prevented and also wavelet based harmonic analysis shows which harmonics occur in which time.

According to their performance on the analysis, complex Morlet "cmor0.5-10" wavelet is the most suitable when it comes to harmonic analysis on a cogeneration plant data. This mother wavelet is appropriate to locate harmonic frequencies accurately. For the de-noising part a level 2 Daubechies wavelet "db 6" is suitable for the thresholding. De-noising algorithm is better than the low-pass filter response and it eliminates harmonics effectively.

All the analysis is developed by using MATLAB and Siemens WinPM data logger. It is only used baseload and island mode data sets. The comparison between these operating modes indicates that there is harmonic flow comes from PCC to the system. In island mode operation, system works perfectly with proper load shedding. In the base load of operation gas turbines generate nearly pure sine waves to feed the system; however non-linear loads and big motors generate harmonic components. If there is harmonic related incident this thesis can be used as a base for deeper analysis.

According to simulation and comparison results, wavelet based harmonic analysis is better a better than Fourier theory and for the harmonic elimination, traditional FIR filters are convenient because of its low cost. De-noising algorithm is useful when there is a sensitive elimination of harmonics.

5.1   FUTURE WORK

The future work will be about different thresholding methods like minimax, Rigorous Sure and HeurSure are used for eliminating harmonic frequencies. Results of this kind of application will be examined and comparisons with other methods in the literature will be obtained.

It is also done a seasonal harmonic analysis with respect to summer and winter conditions. In order to determining seasonal loads, precautions can be taken.

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APPENDIX A

	YER	KURULUŞ ADI	KURULU GÜÇ	YAKIT	
1	İZMİR	AKDENİZ KİMYA SAN. VE TİC. A.Ş.	4.044	DOĞALGAZ	TERMİK
2	İZMİR	ALİAĞA RES (BERGAMA RES ENERJİ ÜRETİM A.Ş.)	90.000	RÜZGAR	RÜZGAR
3	İZMİR	ALİAĞA RES (TAN ELEKTRİK ÜR. A.Ş.)	9.600	RÜZGAR	RÜZGAR
4	İZMİR	ALİAĞA+ÇEVRİM	180.000	DOĞALGAZ	TERMİK
5	İZMİR	ARES (ALAÇATI RÜZGAR)	7.200	RÜZGAR	RÜZGAR
6	İZMİR	ATAER ENERJİ ELEKTRİK ÜRETİM A.Ş. (DG+N)(Ebso)	119.200	SIVI+DOĞALGAZ	TERMİK
7	İZMİR	BATIÇİM BATI ANADOLU ÇİMENTO SAN.A.Ş.(BATIÇİM)	9.000	YENİLENEBİLİR + ATIK+ATIK ISI	TERMİK
8	İZMİR	BOZYAKA RES (KARDEMİR HADDECİLİK VE ELEKT.)	12.000	RÜZGAR	RÜZGAR
9	İZMİR	DELTA PLASTİK (ALİZE ENERJİ RES)	1.500	RÜZGAR	RÜZGAR
10	İZMİR	DESA ENERJİ ELEKTRİK ÜRETİM A.Ş. (D.G.+NAFTA+LPG)	9.813	SIVI+DOĞALGAZ	TERMİK
11	İZMİR	DÜZOVA RES (ÜTOPYA ELEKTRİK)	40.000	RÜZGAR	RÜZGAR
12	İZMİR	EGE SERAMİK ENERJİ SANTRALI (EGE SERAMİK)	13.080	DOĞALGAZ	TERMİK
13	İZMİR	EKOTEN TEKSTİL	1.932	DOĞALGAZ	TERMİK
14	İZMİR	HABAŞ ALİAĞA	224.460	DOĞALGAZ	TERMİK
15	İZMİR	HABAŞ(İZMİR)(Habaş)	36.000	FUEL-OİL	TERMİK
16	İZMİR	İŞBİRLİĞİ ENERJİ ÜRETİM SAN. VE TİC. A.Ş.	19.460	DOĞALGAZ	TERMİK
17	İZMİR	İZDEMİR ENERJİ ELEKTRİK ÜRETİM TESİSİ (İZDEMİR EN.)	350.000	İTHAL KÖMÜR	TERMİK
18	İZMİR	İZMİR	1.590.740	DOĞALGAZ	TERMİK
19	İZMİR	İZMİR BÜYÜK EFES OTELİ KOJENERASYON TES.	1.200	DOĞALGAZ	TERMİK
20	İZMİR	JTI TORBALI KOJENERASYON SANTR. (JTI TÜTÜN)	4.000	DOĞALGAZ	TERMİK
21	İZMİR	KARABURUN RES (LODOS KARABURUN ELEKTRİK)	120.000	RÜZGAR	RÜZGAR
22	İZMİR	KAREGE(ARGES)(DG+FO)(K.Paşa)	43.650	DOĞALGAZ	TERMİK
23	İZMİR	KOJENERASYON SANTRALİ (ALKİM KAĞIT SAN.)	10.700	DOĞALGAZ	TERMİK

	YER	KURULUŞ ADI	KURULU GÜÇ	YAKIT	
24	İZMİR	KORES KOCADAĞ RES (Urla/İZMİR)	17.500	RÜZGAR	RÜZGAR
25	İZMİR	KORKMAZ RES (AYEN ENERJİ)	24.000	RÜZGAR	RÜZGAR
26	İZMİR	KOZBEYLİ RES (DOĞAL ENERJİ ELEKTRİK ÜRETİM)	32.200	RÜZGAR	RÜZGAR
27	İZMİR	KÜÇÜKBAY YAĞ VE DETERJAN SAN. A.Ş.	1.605	DOĞALGAZ	TERMİK
28	İZMİR	MARE MANASTIR RÜZGAR	39.200	RÜZGAR	RÜZGAR
29	İZMİR	MAZI-3 RES (MAZI-3 RES ELEKTRİK ÜRETİM A.Ş.)	30.000	RÜZGAR	RÜZGAR
30	İZMİR	MED UNION (Ebso)	3.380	FUEL-OİL	TERMİK
31	İZMİR	MOPAK (Işıklar)	4.550	SIVI+DOĞALGAZ	TERMİK
32	İZMİR	MORDOĞAN RES (AYEN ENERJİ A.Ş.)	30.750	RÜZGAR	RÜZGAR
33	İZMİR	OTOPRODÜKTÖR SANT. (TÜRKİYE PET.RAF.) İZMİR	49.250	DOĞALGAZ	TERMİK
34	İZMİR	PAK GIDA(Kemalpaşa)	5.670	DOĞALGAZ	TERMİK
35	İZMİR	PANER KOJEN. SANT.(PANCAR ELEKTRİK ÜR.A.Ş.)	37.720	DOĞALGAZ	TERMİK
36	İZMİR	PETKİM ALİAĞA(Aliağa)	222.040	SIVI+DOĞALGAZ	TERMİK
37	İZMİR	SALMAN RES (ÖRES ELEKTRİK ÜR.A.Ş.)	20.000	RÜZGAR	RÜZGAR
38	İZMİR	SAMURLU RES (DOĞAL ENERJİ ELEKTRİK ÜRET.)	34.500	RÜZGAR	RÜZGAR
39	İZMİR	SEYİTALİ RES (DORUK ENERJİ ELEKTRİK ÜRETİM)	30.000	RÜZGAR	RÜZGAR
40	İZMİR	TERMİK-D.GAZ KÇS (ALİAĞA ÇAKMAKTEPE ENERJİ)	268.360	DOĞALGAZ	TERMİK
41	İZMİR	TESKO KİPA KİTLE PAZ. TİC. VE GIDA A.Ş. (Çiğli/İZMİR)	2.330	DOĞALGAZ	TERMİK
42	İZMİR	TİRE-KUTSAN(Tire)	8.000	SIVI+DOĞALGAZ	TERMİK
43	İZMİR	TİRENDA TİRE ENERJİ ÜRETİM A.Ş.	58.380	DOĞALGAZ	TERMİK
44	İZMİR	TÜPRAŞ RAFİNERİ(Aliağa/İzmir)	44.000	FUEL-OİL	TERMİK
45	İZMİR	YUNTDAĞ RES (İNNORES ELEKTRİK) (Aliağa-İZMİR)	60.000	RÜZGAR	RÜZGAR
46	İZMİR	ZEYTİNELİ RES (ZEYTİNELİ RES ELEKTRİK ÜRETİM)	49.500	RÜZGAR	RÜZGAR
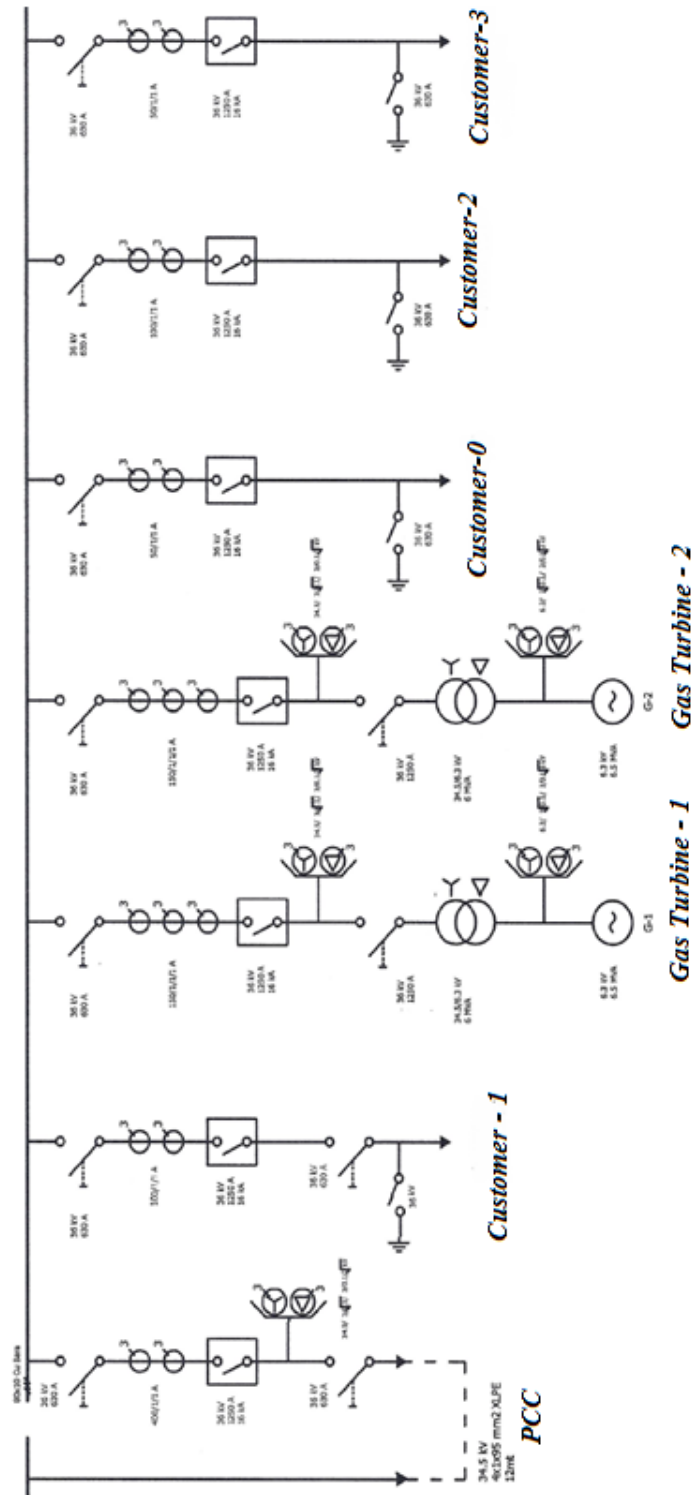
Single Line Diagram of the Plant

<h1 align="center">CURRICULUM VITEA</h1>

<h1 align="center">Güneş BECERİK</h1>

October 2015

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CONFERENCE PRESENTATIONS _____

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