

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**ANOMALY DETECTION
IN ELECTRICAL POWER SYSTEM
USING PHASOR MEASUREMENT UNITS**

M.Sc. THESIS

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Electrical Engineering Programme

MAY 2015

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

Güç Elektrik Sistemlerinde Faz Ölçüm Birimleri Yöntemi İle Anomali Belirlemesi

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MAYIS 2015

To my beloved family,

FOREWORD

I would like to thank my supervisor Professor Dr. Serhat Şeker for giving me valuable advice and support always when needed. Other important persons considering my thesis is Dr. Tahir Cetin Akinci whom I like to give my special thanks for giving me an opportunity to share their knowledge and the best available information about electrical test systems and their theoretical backgrounds.

May 2015

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ABBREVIATIONS

CWT	: Continuous Wavelet Transform
EIPP	: Eastern Interconnection Phasor Project
EMS	: Energy Management System
FT	: Fourier Transform
GPS	: Global Positioning System
MRA	: Multi Resolution Analysis
PA	: Prony Analysis
PDC	: Phasor Data Concatenator
PMU	: Phasor Measurement Unit
PT	: Prony Toolbox
SCADA	: Supervisory Control And Data Acquisition
STFT	: Short Time Fourier Transform
TAI	: International Atomic Time
WAMS	: Wide Area Monitoring System
WT	: Wavelet Transform

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ANOMALY DETECTION IN ELECTRICAL POWER SYSTEM USING PHASOR MEASUREMENT UNITS

SUMMARY

Electrical power system consists of large number of interconnected systems/entities to enable exchange of electrical power from the generating sources to the consumers. Today's grid has transformed into a very complex structure trying to fulfill the ever-growing demand of electrical energy for domestic, commercial and industrial consumers. In addition, electricity market has become quite complex due to incorporation of de-regulated market structure. Although, to achieve the required efficiency, reliability, robustness and performance of the electrical grid, modernized control system is deployed. Still we are observing blackouts, instabilities in our electrical grid. Since every market player wants to gain maximum profits. So generally in deregulated market structure, players always trying to produce maximum when rates are high and used to shut down facilities in low price periods. This makes power system operators to run their system up to its limits leaving a small margin for instabilities. In the recent past years, major blackouts in the developed and the developing countries rang the alarm bells for the development of new technologies to avoid the cascading loss of power supplies after some faults or generation loss. Hence, more refined procedures and advanced monitoring techniques are required to develop so that customer satisfaction is achieved for electrical commodity.

Although, it is impossible to wipe out the blackouts completely from the power system. However, research in Wide Area Monitoring System (WAMS), being an emerging concept, will help in avoiding or minimizing the chances of occurrence of blackouts and power system outages at the mass scale. Introduction of Phasor Measurement Units, having reporting rate of 20-60 times in a second, made it possible to track electrical grid dynamics in real time which was not possible with conventional deployed SCADA (whose refresh rate is from seconds to minutes). New techniques and tools are required to utilize this high-resolution data to extract useful information and state of the system. Generally, these techniques falls under the category of Wide Area Monitoring System (WAMS), in which GPS time synchronized signals namely voltage (magnitude & phase), current (magnitude & phase), frequency obtained at different nodes/buses of the power system through PMUs.

Energy Management System (EMS) by incorporating the WAMS can provides system operator sufficient information that includes normal steady state system operation, slow changes in the operating conditions and system dynamics (when the system is subjected to large disturbances). In addition, off-line studies can be used to simulate different scenarios and conditions faced by operators to enhance their analyzing capabilities. WAMS also provides several control applications e.g. control for electrical machines were achieved by feedback signals obtained by local measurement devices. Sometimes, even mathematical models are used to achieve the

same. However, using PMUs, machines can be controlled by incorporating the remote measurement e.g. basing on slow changing oscillations occurring in the system. In addition, PMU measurements provide protecting functions related to distance relays, angular stability, voltage stability etc. by incorporating the remote measurements because of low propagation delays having very low latencies.

Normally in PMU applications, data is collected from the PMUs installed in the field or some studies just utilized the phasor simulation environment to get the phase and magnitude of the analyzed quantities. However, this study provides the pioneer approach to utilize the PMU's data measured by the Matlab PMUs model. Hence, virtual analysis can be carried out considering different scenarios that is impossible in the real time system operation.

In this study using MATLAB SIMULINK simulation environment is used to detect anomalies like inter-area oscillations, ferroresonance etc. utilizing several signal processing techniques for feature extraction. This will provide a virtual experimental setup (test-bed) to simulate various scenarios so that analysis can be carried out to detect any undesirable situation in the power system operation.

In the first simulation setup, machines stability analysis was carried out using the outputs obtained through the Simulink-PMU model installed at the respective buses of machines. Electromechanical oscillations have been a topic of interest for researchers since many years. Generally, power system stabilizers are used to counter the condition of insufficient damping. Power system stabilizers controls generator output by changing the set point of the voltage regulator. Traditionally, this close loop feedback control is based on the locally measured signals such shaft rotational speed, real power output and frequency. Events and their features extractions were analyzed using the spectral measuring techniques in time, frequency and time-frequency domains e.g. Short Time Fourier Transform, Continuous Wavelet Transforms etc. Furthermore Prony analysis was applied on the acquired signals for identification of oscillation properties i.e. mode frequency, mode damping, and mode shape. Scenarios were created by applying faults, load changes while keeping power system stabilizer (PSS) on different setting. Moreover, impacts of all scenarios were investigated using the foresaid analysis techniques.

Second simulation setup of this study involves the application of the Simulink model of Phasor Measurement Unit (PMU) for the detection of ferroresonance phenomenon for the Seyitomer–Isiklar part of the Electric Power System of 380 kV in Turkey using signal analysis techniques in time, frequency and time-frequency domains. The ferroresonance phenomenon is one of the critical problems occurring in electrical power systems. In ferroresonance condition over-voltages are observed in the power system. Ferroresonance phenomenon is generally nonlinear in nature. The ferroresonance phenomenon generally occurs due to unbalanced condition such as switching, the serial connections of the capacitors with transformer magnetizing impedance etc. These over voltages cause failures in transformers, cables, and arresters. The findings show that the ferroresonance event can be represented by the interharmonics between 50 and 250 Hz. These analysis techniques will result in better monitoring, identification and helps to take prevention measures to avoid undesirable condition in the power system operation.

It has been shown through the simulated scenarios i.e. detection of inter-area oscillations and ferroresonance phenomenon, that PMUs measurement can successfully achieved the desired results. These applications along with other similar

one in Wider Area Monitoring System provides the promising future which will ensure better monitoring, control and grid management on the whole. Blackouts can be avoided through the situational awareness provided by the PMUs. Hence, grid can be operated with enhanced reliability. In short, WAMS reliable detection and monitoring of power system oscillations will be one of the most critical applications of the future power networks. So that a valuable information of increasing oscillations and instability be provided to the system operators and detection algorithms. In addition, operator can be alerted to observe and monitor the synchronized phasor measurements to find the root cause of instability by comparing the data and events occurred during the same time instants. Also, corrective actions can be taken to safe guard the further instability

Further few recommendations were given for the deployment of PMUs in Turkish Grid to get benefit from these reliable emerging applications of WAMS:

- Hybrid setup should be built using the conventional SCADAs and PMUs together to gain the trust of system operators.
- Studies should be carried out in Turkish grid and system operators should be consulted for deployment of PMUs on the all critical nodes of the system.
- More robust state estimation techniques should be developed to enhance the dynamic event capturing capability of PMUs.
- Also a research setup should be developed so that real time values can be obtained for further studies on actual system.

Güç Elektrik Sistemlerinde Faz Ölçüm Birimleri Yöntemi İle Anomali Belirlemesi

ÖZET

Elektrik güç sistemi, çok sayıdaki enterkonekte sistemlerden oluşan ve üretici kaynaklarından tüketiciye, enerji transferini sağlayan büyük bir sistemdir. Günümüz itibari ile bu şebekeler lokal, ticari ve sanayi sektörlerinde tüketicilerin elektrik enerjisine olan sürekli artan talebini karşılamaya çaba gösteren, çok karmaşık bir yapıya dönüşmüştür. Buna ek olarak, düzensiz pazar yapısının olması nedeniyle de elektrik enerji piyasası daha da karmaşık hale gelmiştir. Bilindiği gibi, elektrik şebekelerinde gerekli olan verimlilik, güvenilirlik, sağlamlık ve yüksek performansı elde etmek için, modern kontrol sistemleri kullanılır. Buna rağmen yine de elektrik şebekesinde kesintilere, kararsızlıklara tanık olunur.

Çok iyi bilindiği gibi piyasalarda, her borsa oyuncusu maksimum kar elde etmek ister. Bu yüzden genellikle düzensiz market yapılarında, fiyatlar yüksek olduğu zaman maksimum üretim sağlamaya ve düşük olduğu dönemler de ise tesisleri kapatmaya çalışırlar. Bu nedenle, güç sistemi operatörleri kendi sistemlerini istikrarsızlıklara karşı küçük bir marj bırakarak çalıştırmak isterler. Son yıllarda bazı ülkeler büyük kesintilerin çoğalmasını ve güç kaybını önlemek adına yeni teknolojilerin geliştirilmesi için araştırmalara yeni bütçeler ayırmaya başlamıştır. Bu nedenle de elektrik şirketleri müşteri memnuniyetini kazanmak için daha rafine işlemleri ve gelişmiş izleme tekniklerinin geliştirilmesi üzerine yoğunlaşmışlardır. Güç sisteminden elektrik kesintisini tamamen yok etmek imkansız olsa da, ancak Geniş Alan İzleme Sistemleri (Wide Area Monitoring Sytem-WAMS) üzerine olan araştırmalar, kesintilerin ve güç sisteminde kitlesel ölçekte kesintilerin meydana gelme olasılığını önlemek veya en düşük seviyeye indirilmesine yardımcı olacak bir kavram olarak gelişmektedir.

Günümüzde Fazör Ölçüm Birimleri (PMU-Phasor Measurement Unit) saniyede 20-60 kez raporlama hızı ile geleneksel konuşlandırılmış SCADA (kendilerini yenileme hızı saniyeler ile dakikalarca sürüyor) ile mümkün olmayan gerçek zamanlı elektrik şebekesi dinamiklerinin izlenmesini mümkün kılmıştır. Bunun için yüksek çözünürlüklü verileri kullanarak sistemin faydalı bilgiler ve durumunu ayıklamak için yeni teknikler ve araçlar gereklidir. Genellikle, bu teknikler Geniş Alan İzleme Sistemi (WAMS) kategorisinde yer alır. Burada, farklı şebeke düğümlerinden gelen sinyaller için GPS, gerilim (genlik ve faz), akım (genlik ve faz) ve frekans değerleri için, Güç sistemi PMU'lar aracılığıyla zaman senkronizasyonu yapar. Enerji Yönetim Sistemi (EMS-Energy Management System), WAMS katılımıyla sistem operatörüne yeterli bilgi sağlar ve bu bilgiler normal kararlı durumda olan sistemin çalışmasını, çalışma koşullarında yavaş değişimlerini ve sistem dinamiğini (sistem büyük dalgalanmalara maruz bırakıldığında) kapsar. Buna ek olarak, çevrimdışı çalışmaları, operatörlerin karşılaştığı farklı senaryoları ve koşulları simüle etmek ve onların analiz yeteneklerini geliştirmek için de kullanılabilir.

WAMS tekniđi ayrıca çeřitli kontrol uygulamalarına da olanak sađlar. Örneđin, lokal ölçüm cihazları vasıtasıyla elde edilen geri-bildirim sinyalleri elektrik makinelerinin kontrolü, hatta bazı durumlarda matematiksel modelleri için kullanılır. Bununla birlikte, PMU' lar kullanılarak uzaktan ölçüm yoluyla (örneğin sistemde meydana gelen yavaş deđişen osilasyonlara dayanan) Makineler kontrol edilebilir. Ayrıca PMU ölçümleri, çok düşük gecikmeleri ve düşük yayılım gecikmeleri olan uzak ölçülerin katılmasıyla mesafe rölelerine, açılabilir stabiliteye, gerilim kararlılığına vb ye ilişkin koruma fonksiyonlarını da sađlar. Normalde PMU uygulamalarında, veriler alanda kurulan PMU' lardan toplanır, ya da bazı çalışmalar sadece analiz edilen büyüklüklerin fazını ve genliğini elde etmek için fazör simülasyonunu kullanır.

Bu tez çalışması, Matlab PMU' lar modeli ile ölçülen PMU verilerini kullanarak öncü bir yaklaşım sağlamıştır. Bu çalışmada MATLAB SIMULINK' in simülasyon ortamında, özellik çıkarımı için çeřitli sinyal işleme teknikleri kullanılarak bölgeler arası (inter-area) osilasyonlar, ferrezonans vb gibi anormallikler tesbit edilmiştir. Çeřitli senaryoları simüle etme amacıyla bir sanal deney düzeneđi (test-bed) sağlanarak, güç sistemi operasyonlarında herhangi bir istenmeyen durum tespit analizinin gerçekleştirilebilirliği amaçlanmıştır.

İlk güç sistemi simülasyon çalışmasında, Simulink-PMU modeli ile makinelerin ilgili kurulu baralarında ki çıkışlardan elde edilmiş bilgiler kullanılarak makinelerin kararlılık analizi gerçekleştirilmiştir. Yıllardan beri Elektromekanik salınımlar araştırmacılar için ilgi çeken bir konu olmuştur. Genellikle, bu konuya ilişkin olarak, güç sistemi stabilizatörleri makinelerin yetersiz sönümlenmelerine karşı, kararlılık analizi gerçekleştirilmesi için kullanılırlar. Güç sistemi stabilizatörleri voltaj regülatörünün set noktasını deđiştirerek, jeneratörün çıkışını kontrol eder. Geleneksel olarak, bu kapalı döngü geri besleme kontrolü, lokal olarak şaftın dönme hızı, gerçek güç çıkışı ve frekansdan ölçülen sinyallere dayanmaktadır. Olaylar ve özellik çıkarımları zaman ve spektral domenlerdeki hesaplama teknikleri kullanılarak zaman, frekans ve zaman-frekans bölgelerinde (örneğin Kısa Zaman Fourier Dönüşümü, Sürekli Dalgacık Dönüşümü vb) analiz edilerek saptanmıştır. Ayrıca, salınım özellikleri, mod frekansı, mod sönümlenme ve mod şeklini tanımlamak için edinilen sinyallere Prony analizi uygulanmıştır. Güç sistemi sabitleyicilerini (PSS) farklı ayarda tutarak yapay arızalar ve yük deđişiklikleri uygulanarak senaryolar oluşturulmuştur. Tüm senaryolar ve etkileri yukarıda bahsedilen analiz teknikleri yoluyla araştırılmıştır.

Bu çalışmanın ikinci simülasyon örneđi, Türkiye' de 380 kV Elektrik Sistemi Seyitömer-İşıklar kısmı için ferrezonans olgusunun belirlenmesinde zaman, frekans ve zaman-frekans etki sinyal analiz teknikleri kullanılarak, Fazör Ölçüm Birimi (PMU) Simulink modeli uygulamasıdır. Ferrezonans olayı elektrik sistemlerinde meydana gelen önemli sorunlardan biridir. Ferrezonans durumunda güç sisteminde aşırı gerilim görülmektedir. Genellikle Ferrezonans doğal olarak lineer olmayan bir fenomendir. Ferrezonans olayı genellikle dengesiz durumlarda, örneđin anahtarlama, kondansatörlerle trafo mknatıslama empedanslarının seri bağlantıları vb gibi nedenlerden oluşur. Böylece oluşan aşırı gerilimler transformatörler, kablolar ve tutucularda arızalara yol açar. Bulgular ferrezonans olayını 50 ve 250 Hz arasındaki ara harmonikler tarafından temsil edilmesini göstermektedirler. Bu tez çalışmasında kullanılan analiz teknikleri daha iyi izleme ve tanımlamaya neden olacaktır, aynı zamanda güç sistemi çalışmasında istenmeyen durumlarda önleme tedbirleri almaya da yardımcı olacaktır. Simülasyonlara dayalı

senaryolar aracılığıyla, PMU'larda ölçülen bölgeler arası (inter-area) salınımların ve ferrerezonans olaylarının saptanması bu tez çalışmasında da başarı ile gösterilmiştir.

Geniş Alan İzleme Sistemi ve kontrol gibi diğer uygulamalarla birlikte şebeke yönetimine bir bütün olarak bakıldığında, daha güvenilir bir şebeke yönetimi için umut verici bir gelecek sağlayacaktır. Elektrik kesintileri PMU'lar tarafından sağlanan durumsal farkındalık yoluyla önlenebilir. Böylece şebeke geliştirilmiş güvenilirliğe sahip olarak çalıştırılacaktır. Kısacası, WAMS güç sistemi salınımlarının güvenilir olarak izlenmesi ve tesbiti gelecekteki güç şebekelerinin en kritik uygulamalarından biri olacaktır. Ayrıca, sistem operatörleri ve algılama algoritmaları için artan titreşimler ve istikrarsızlıklardan da değerli bilgiler sağlanacaktır. Bu sistem gözetimin sağladığı bir deneyim olarak, operatörler için faydalı bir bilgiye dönüştürülebilir. Böylece operatörler eşzamanlı anlar sırasında oluşan veri ve olayları karşılaştırarak istikrarsızlığın ana nedenini bulmak üzere gözlem yapmak ve senkronize fazör ölçümlerini izlemek için uyarılabilir. Ayrıca, gelecekteki istikrarsızlıklardan korunmak için düzeltici eylemler de devreye alınabilir. Bütün bunların ötesinde WAMS'ın geliştirmekte olan güvenilir uygulamalarından faydalanmak için Türkiye şebekesinde PMU'ların konuşlandırılması ile ilgili birkaç öneri de sunulmuştur:

- Sistem operatörlerinin güvenini kazanmak için konvansiyonel SCADA ve PMU'lar kullanarak, melez kurulum inşa edilmelidir.
- Çalışmalar Türkiye şebekesinde yapılmalıdır ve sistemin tüm kritik düğümlerinde PMU'ların konuşlandırılması için operatörlere danışılmalıdır.
- PMU'ların dinamik olay yakalama yeteneğini geliştirmek için daha sağlam durum tahmin teknikleri geliştirilmelidir.
- Gerçek zamanlı değerlerin gelecekteki ileri çalışmalar için kullanılabilmesi amacıyla, bu konuda bir araştırma kurumu da geliştirilmelidir.

1. INTRODUCTION

Electrical power system consists of large number of interconnected systems/entities to enable exchange of electrical power from the generating sources to the consumers. Starting from the first electrical power system which was built in 1881 by two electricians in Goldming England to power up 34 incandescent lamps at 40 volts.[1] Today's grid has transformed into a very complex structure trying to fulfill the ever-growing demand of electrical energy for domestic, commercial and industrial consumers. Although, to achieve the required efficiency, reliability, robustness and performance of the electrical grid, modernized control system is deployed. Still we are observing blackouts, instabilities in our electrical grid. Since every market player wants to gain maximum profits. So generally in deregulated market structure, players always trying to produce maximum when rates are high and used to shut down facilities in low price periods. This makes power system operators to run their system up to its limits leaving a small margin for instabilities. In the recent past years, major blackouts in the developed and the developing countries rang the alarm bells for the development of new technologies to avoid the cascading loss of power supplies after some faults or generation loss. Hence, more refined procedures and advanced monitoring techniques are required to develop so that customer satisfaction is achieved for electrical commodity.

1.1 Purpose of Thesis

Introduction of Phasor Measurement Units, having reporting rate of 20-60 times in a second, enabled to track electrical grid dynamics in real time which was not possible with conventional deployed SCADA (whose refresh rate is from seconds to minutes). New techniques and tools are required to utilize this high-resolution data to extract useful information about the state of the system. In this study I will be focusing on several signal processing techniques for feature extraction from the signals obtained from the PMUs to detect anomalies like inter-area oscillations, ferroresonance etc. Simulation environment will be developed using MATLAB SIMULINK for the qualitative and parametric identification of the abnormalities. This will provide a virtual experimental setup (test-bed) to simulate various scenarios so that analysis can be carried out to detect valuable information to avoid any undesirable situation in the power system operation.

1.2 Motivation

Today's electrical power systems are quite smart. SCADA and EMS system are functional providing exchange of useful information and control capabilities. However, mainly these technologies rely on model-based structure. In addition, these facilities are quite satisfactory in steady state operations. However, current advancements in communication technologies provide very fast, efficient and

reliable exchange of information. Phasor measurement technology using these modern communications means gives an alternative way of analysis using measurement based structure i.e. to extract useful information from the measurements received from PMUs. In this study, a virtual environment is selected so that experiments can be made to validate the outcomes of the measurement based structure with the well-defined and already developed model based applications. Following section will give brief information about the blackouts and SCADA vs. PMU comparison.

1.2.1 Blackouts

Blackouts are generally rare events occurring in power system. However, cost of the losses incurred and number of customers that are affected is very high. In the recent past years, major blackouts in the developed and the developing countries rang the alarm bells for the development of new technologies to avoid the cascading loss of power supplies after some faults or generation loss. Data of few noticeable power blackouts is given in the Table 1.1.

Table 1.1 : Data of few noticeable Power Blackouts.

Location	Date	No. of People Affected (Millions)	Reference
Turkey	31 Mar 2015	76	Url-1
Pakistan	25 Jan 2015	140	Url-2
Bangladesh	1 Nov 2014	150	Url-3
India	30-31 Jul 2014	600	Url-4
Indonesia	18 Aug 2015	100	Url-5
USA, Canada	14-15 Aug 2003	55	Url-6

Although it is impossible to wipe out the possibilities of blackouts completely from the power system. However, research in Wide Area Monitoring System (WAMS), being an emerging concept, will help in avoiding or minimizing the chances of occurrence of blackouts and power system outages at the mass scale. A brief description of the same will be given in the coming sections.

Energy Management System (EMS) by incorporating the WAMS can provides system operator sufficient information that includes normal steady state system operation, slow changes in the operating conditions and system dynamics (when the system is subjected to large disturbances). In addition, off-line studies can be used to simulate different scenarios and conditions faced by operators to enhance their analyzing capabilities.

1.2.2 PMUs vs. SCADA

PMUs make measurements with high resolution in time (e.g. 30 samples per second) which is significantly faster than the conventional SCADA system, which makes measurements only every few seconds. Hence, PMUs can provide more insight into the system dynamics, which was not possible with the previous SCADA technology. An example of an event of voltage disturbance occurred on 5th-April-2011 in the Oklahoma Gas & Electric is given in below Figure-1.1 below.

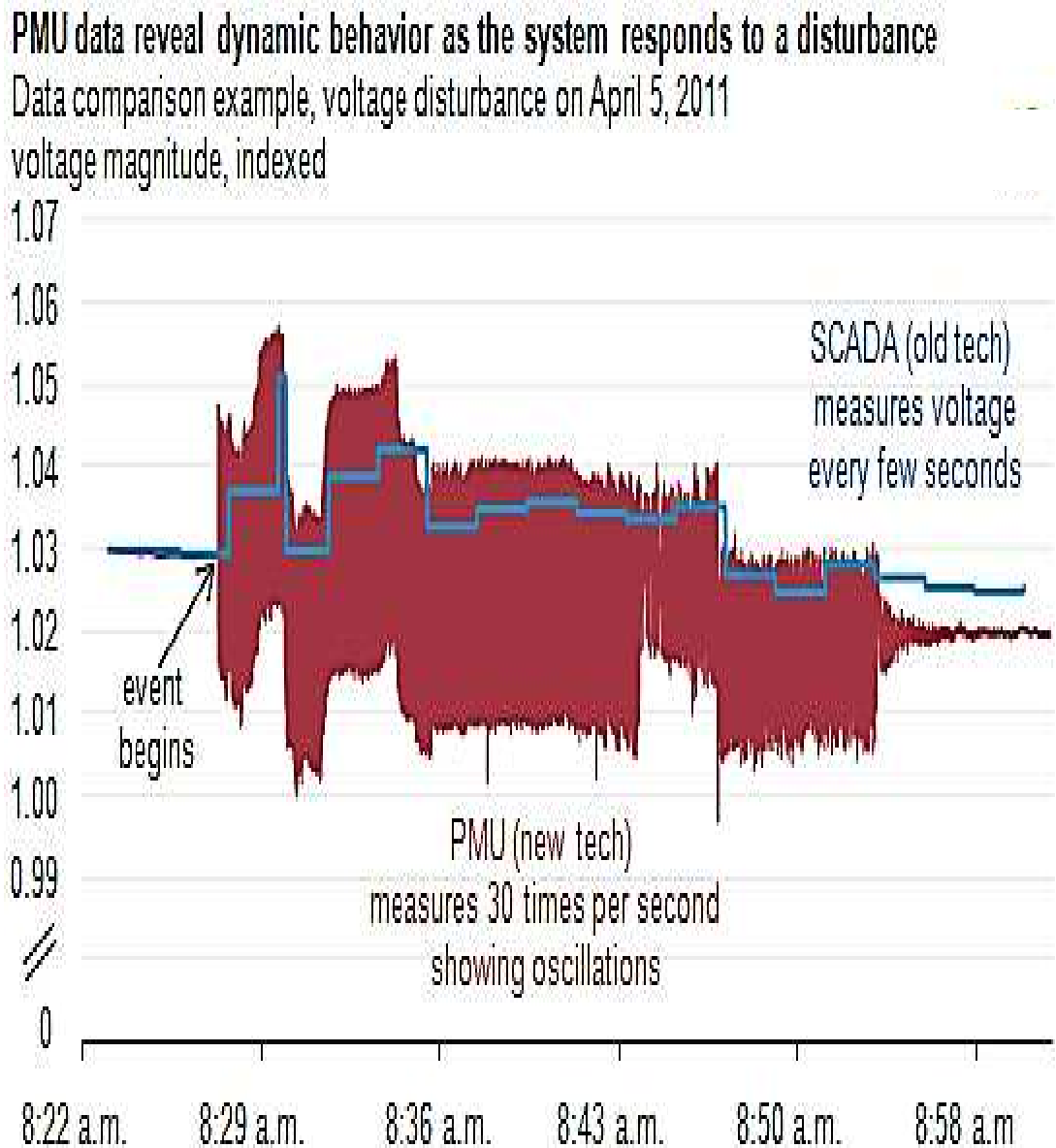


Figure 1.1 : Comparison of PMU and SCADA of voltage magnitude courtesy of U.S. Energy Information Administration, based on Oklahoma Gas & Electric system disturbance data[2]

Another example is taken shows that SCADA because of the it is low scan times misses the important dynamic information of the event which is easily captured by the corresponding PMU recorded data. Pictorial comparison of the event is given in figures below:



Figure 1.2 : Change in frequency captured by SCADA [3]

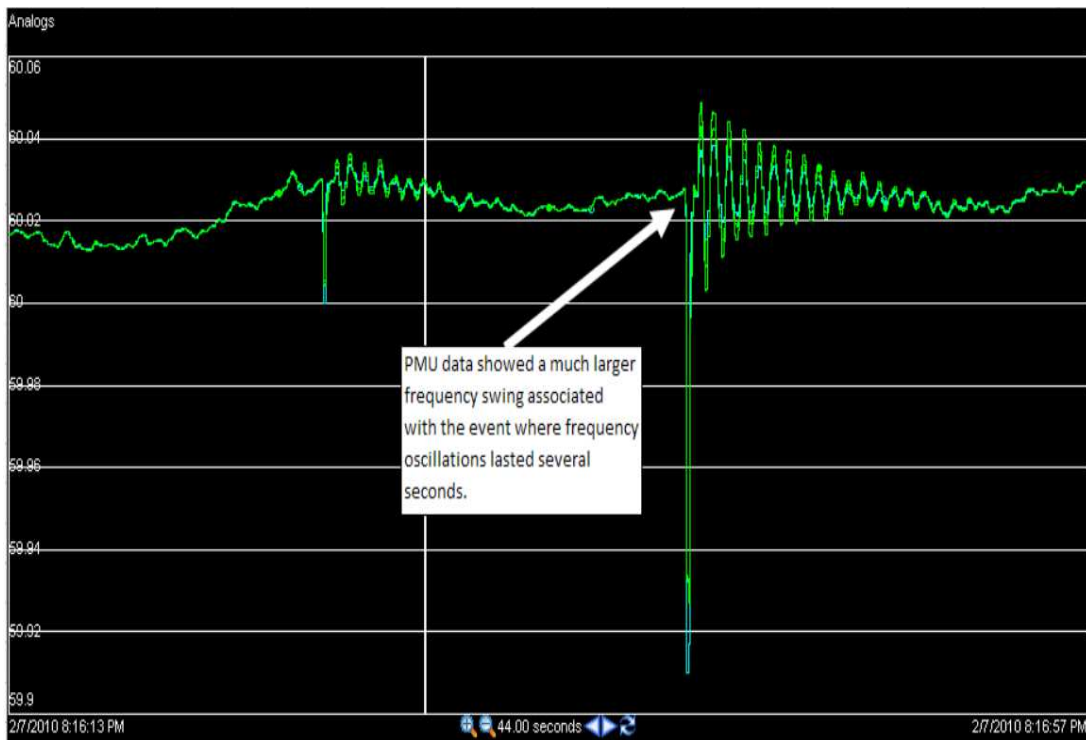


Figure 1.3 : Corresponding change in frequency measured by PMU [3]

From Figures 1.2 & 1.3, it is revealed that variation in frequency captured by PMU is from 59.91 Hz to 60.05 Hz. However, SCADA captured the same event of change in frequency with the excursion from 60 Hz to 60.05 Hz. Hence, SCADA missed quite valuable dynamic information.

Overall PMUs can be used in measured based signal processing applications by capturing the dynamics and helps in avoiding the blackouts using early warning systems.

1.3 Literature Review

A brief background about Wide Area Monitoring System and its applications is given in the following sections.

1.3.1 Wide area monitoring system

Wide Area Monitoring System (WAMS) is a data acquisition technique in which GPS time synchronized signals namely voltage (magnitude & phase), current(magnitude & phase), frequency obtained at different nodes/buses of the power system through PMUs. These signals are concatenated through Phasor Data Concatenators (PDCs) and transmitted through communication network to central monitoring/control station (EMS). This data can be monitored in real time and stored in the data server for post disturbance analysis when required. Currently real time applications for early warning system using PMUs data for anomalies in the power system are in research and development phase [4].

A schematic setup of WAMs based on Eastern Interconnection Phasor Project (EIPP) community in the USA[5] is given in following figure:

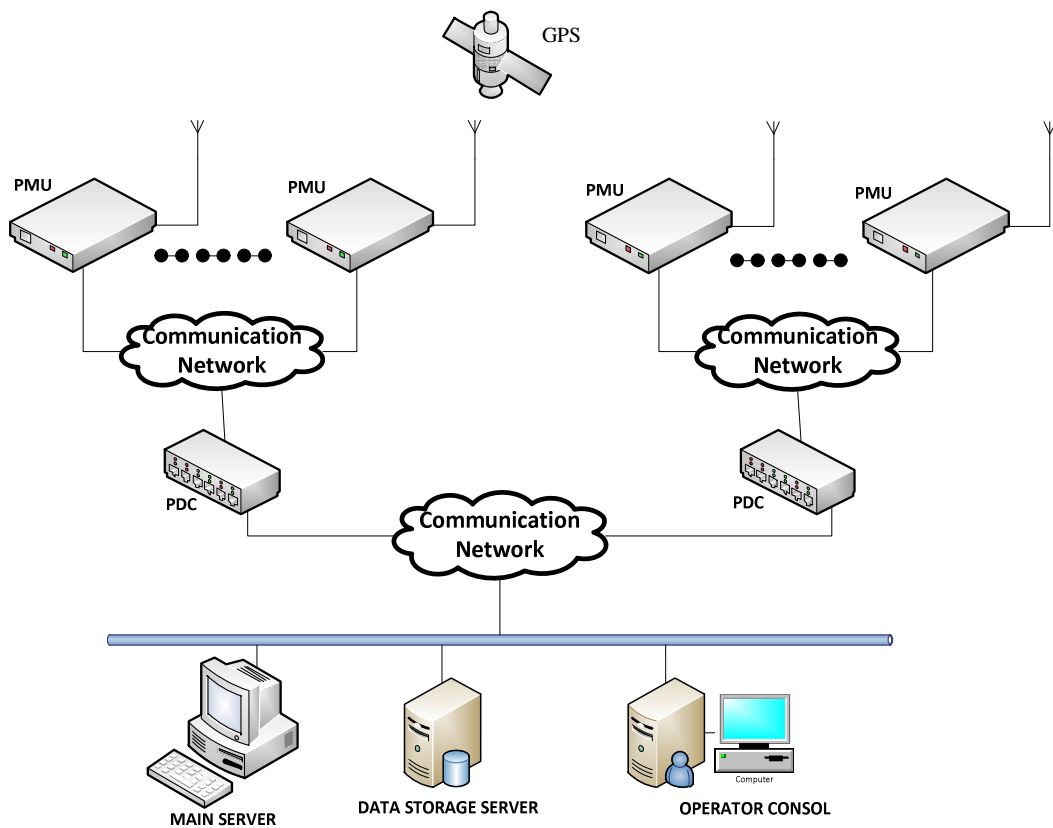


Figure 1.4 : Conceptual Model of WAMS

1.3.2 Wide area monitoring system applications

Few applications developed using Wide Area Monitoring Systems are given in below section.

1.3.2.1 State estimation

In WAMs, we can estimate the dynamic state of the system at an instant in time using the synchronized measurements obtained from PMUs. The perfect scenario would have been to install PMUs at every node of grid to make it completely observable but this is an expensive approach. Several techniques are developed for optimal allocation of PMUs using different estimating techniques without compromising the measurement of that state of the system [6-8]. However, sometimes we need redundancy to eliminate the bad data. Currently a hybrid data state estimate approach which involves both conventional SCADA and PMU measurements[9, 10].

1.3.2.2 Control applications

Conventional control approaches in power system using local signals. For examples control for electrical machines were achieved by feedback signals obtained by local measurement devices. Sometimes, even mathematical models are used to achieve the same. However, using PMUs, machines can be controlled by incorporating the remote measurement e.g. basing on slow changing oscillations occurring in the system [11]. Also system under the instability condition can be isolated in different regions to operate in island mode basing on the information of machines oscillating with similar modes [12]. Hence, wide blackout of the system can be avoided.

1.3.2.3 Protection applications

PMU measurements also provide protecting functions related to distance relays, angular stability, voltage stability etc. by incorporating the remote measurements because of low propagation delays having very low latencies [13, 14].

1.4 Structure of the Thesis

This study is organized as below:

Chapter-1 briefly gives the background about the importance of PMU measurement, WAMS and its applications.

Chapter-2 briefly describes the basis of phasors along with the structure of PMU and its simulation environment.

Chapter-3 briefly gives the mathematical background of the signal processing techniques used in the development of applications e.g. for inter-area oscillation detection and ferroresonance phenomenon etc.

Chapter-4 describes the simulation platform and results obtained by applying signal processing techniques on the data obtained from PMUs in different scenarios.

Chapter-5 gives the conclusion part of this research along with the future recommendations.

2. PHASOR MEASUREMENT TECHNOLOGY

History of phasor representation of electrical quantities dates back to 1893, when Charles Proteus Steinmetz, a German born American mathematician and electrical engineer, represented electrical current in simple form which he named as phasor in his study[15]. Phasor Measurement Units were developed almost a century later in 1988 by Dr. Arun G. Phadke and Dr. James S. Brief detail of mathematical background and PMUs is given in following sections.

2.1 Phasors

Electrical quantities like voltage & current can be modeled by magnitude and angle assuming the frequency being known e.g. 50 Hz or 60 Hz. Consider a sinusoidal signal:

$$x(t) = X_m \cos(\omega t + \varphi) \quad (2.1)$$

Where, X_m is the amplitude, ω is the frequency (radians per second), and φ is phase angle (radians) of the signal $x(t)$. In phasors quantities we are generally interested in the root mean square (RMS) value of the input signal is $(X_m/\sqrt{2})$. It is particularly useful in calculating active and reactive power in an AC circuit. Equation 2.1 in exponential form can be given as follows:

$$x(t) = \text{Re}\{X_m e^{j(\omega t + \varphi)}\} = \text{Re}\{[e^{j(\omega t)}] X_m e^{j(\varphi)}\} \quad (2.2)$$

It is understood for electrical signals that frequency is ω so it is customary to ignore the term $e^{j(\omega t)}$ in the above Equation 2.2. The sinusoidal signal given in Equation 2.1 in corresponding phasor representation is given as:

$$x(t) \leftrightarrow X = (X_m/\sqrt{2})e^{j(\varphi)} = (X_m/\sqrt{2})[\cos\varphi + j\sin\varphi] \quad (2.3)$$

Visual depiction of sinusoidal signal and its corresponding phasor form is shown in Figure 2.1.

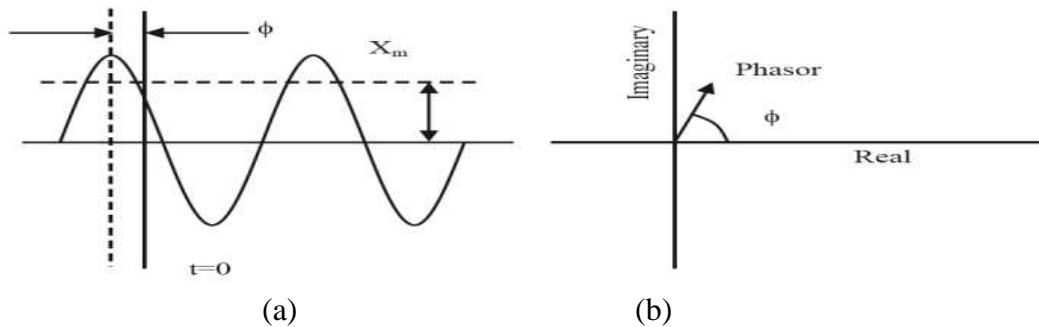


Figure 2.1 : (a) A sinusoidal signal (b) and its corresponding phasor form

2.2 Phasor Measurement Unit

Phadke introduced the Modern synchronized phasor measurement technology in his article [16]. He presented a few uses of positive sequence voltage and current phasor measurements. The Global Positioning System (GPS) provides the reference for the power signals that are measured from different locations can be utilized for analysis. First prototype of PMU based on GPS was developed by the Virginia Polytechnic Institute and State University (Virginia Tech) in the USA in early 1980s. However, modern GPS PMU technology is based on IEEE standard published in 2005.

More refined standards for estimation of positive sequence voltage magnitude, phase, frequency and rate of rise of frequency were published later as IEEE C37.118.1[17] and IEEE C37.118.2 (Data Transfer)[18]. More strict requirements were laid down to achieve required response to dynamic events and measure the harmonic contents of the signals. To achieve the accuracy requirements TVE (Total Vector Error) was set as 1 for frequency and rate of change of frequency. Furthermore an estimation algorithm basing on the above standards and testing was made under the EMRP EURAMET programme [19].

2.2.1 Block diagram of the C37.118.1 algorithm

Schematic block diagram of the C37.118.1 algorithm is given as follows:

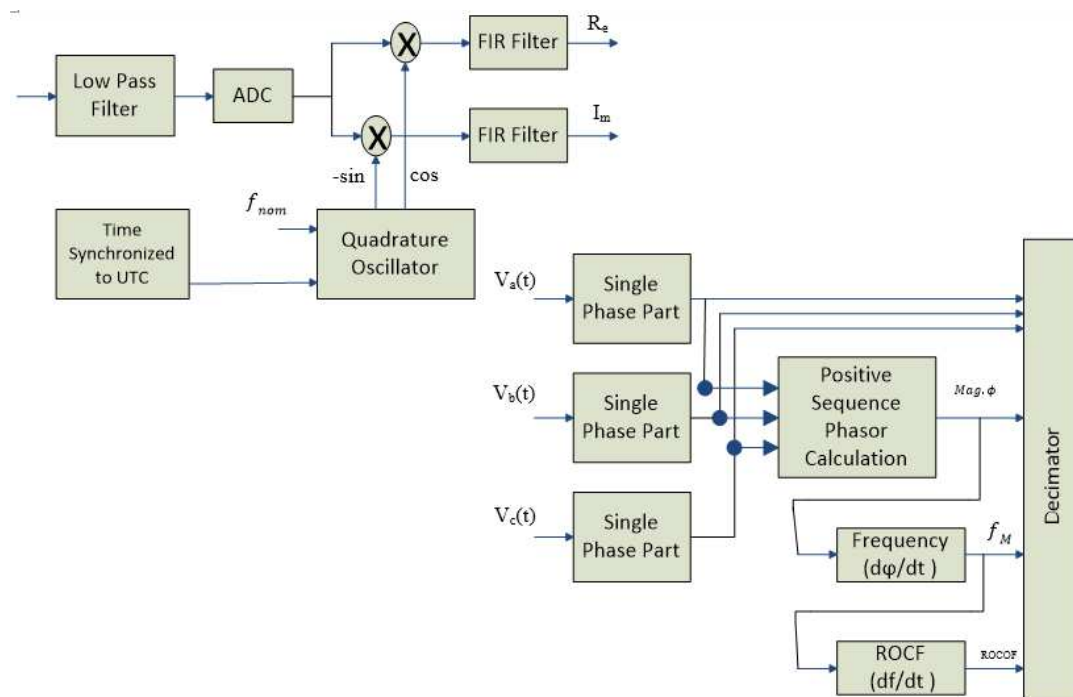


Figure 2.2 : Block diagram of algorithm C37.118.1

Where f_{nom} is the nominal frequency (50 or 60 Hz), Mag, ϕ is the positive sequence phase, f_M is the measured frequency and ROCOF if the rate of change of measured frequency (f_M).

Schematic diagram defines the overall working of a PMU. Input signals are correlated with the output quadrature oscillator at nominal frequency. Each single-phase part generates magnitude proportional to the voltage on each phase, and a phase that rotates at a rate of $2\pi(f - f_0)$.

Low pass filter is used at the input for anti-aliasing. Aliasing is the phenomenon that frequencies greater than the Nyquist frequency are shifted erroneously to lower frequencies. Following equation is used to calculate the Nyquist frequency:

$$f_{Nyquist} = \text{sampling rate}/2 \quad (2.4)$$

The only way to protect data from aliasing is to apply appropriate aliasing protection before you generate or acquire data. Aliasing occurs when you generate or sample the data. You cannot remove aliased components from the data without detailed knowledge of the original signal. In general, you cannot distinguish between true frequency components and aliased frequency components. Therefore, accurate frequency measurements require adequate aliasing protection.

The reporting rate specifies the reporting frequency of the PMU in frames per second. Valid reporting frequencies are 10 fps, 25 fps, and 50 fps for 50 Hz nominal line frequency and 10 fps, 12 fps, 15 fps, 20 fps, 30 fps, and 60 fps for 60 Hz nominal line frequency as defined in IEEE Std C37.118.1

Time synchronization block specifies the timestamps of each sample in the current data block of the input signal. The timestamp is the number of seconds since the International Atomic Time (TAI) epoch of 00:00:00, January 1, 1970, UTC time.

Frequency of the input signal is calculated by:

$$f = \frac{1}{2\pi} \frac{d\varphi}{dt} \quad (2.5)$$

where φ is the measured phase. The time rate of phase helps in calculating even tiny amounts of ripple or noise because a small change in φ can cause large ripple or noise on the measurement of frequency. Further, ROCOF is calculated as follows:

$$ROCOF = \frac{df}{dt} = \frac{1}{2\pi} \frac{d^2\varphi}{dt^2} \quad (2.6)$$

This calculation is very important and used in comparison of signals with each other in Phasor Data Concatenators.

2.2.2 Matlab simulink model of PMU

Normally in PMU applications, data is collected from the PMUs installed in the field. Also, some studies utilized just the phasor simulation environment to get the phase and magnitude of the analyzed quantities. But this study provides the pioneer approach to utilize the PMU's data measured by the Matlab PMUs model as shown in Figure 2.3. Hence, virtual analysis can be carried out considering different scenarios, which is impossible in the real time system operation.

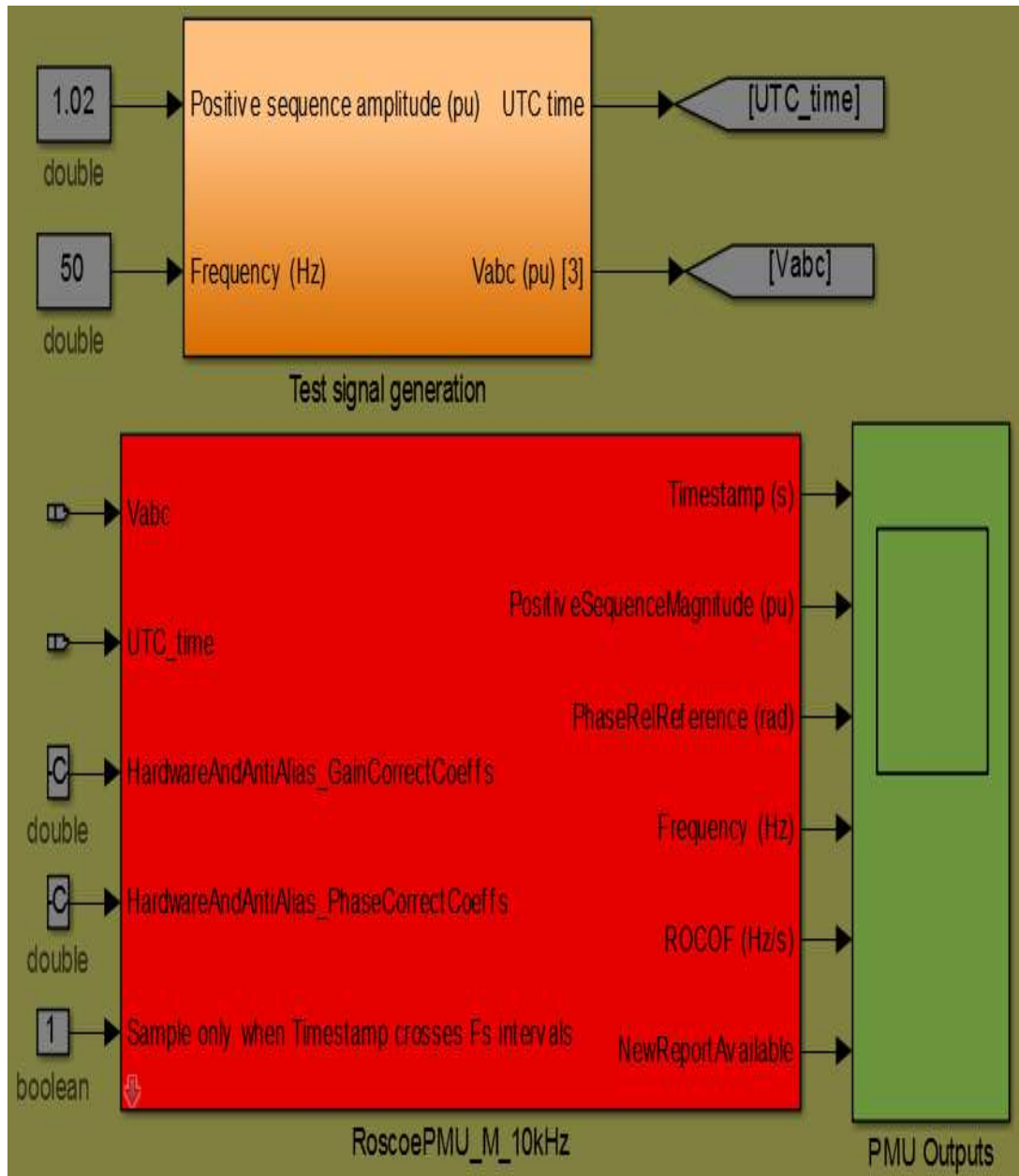


Figure 2.3 : PMUs model in MATLAB simulink by Andrew Roscoe [6]

Following are the inputs of the PMU model as shown in the Figure 2.3:

- Voltage Signal (Vabc)
- GPS Time Stamp (UTC_time)
- Configuration settings (Hardware and Anti Alias Gain & Phase Correction Coefficients)

PMU block, as per the C37.118.1 algorithm, generates the outputs following outputs:

- Magnitude (Positive Sequence Magnitude)
- Phase (Phase Reference)
- Frequency
- ROCOF

Results of the sample case having voltage magnitude of 1.02 p.u., frequency of 50 Hz are given as follows:

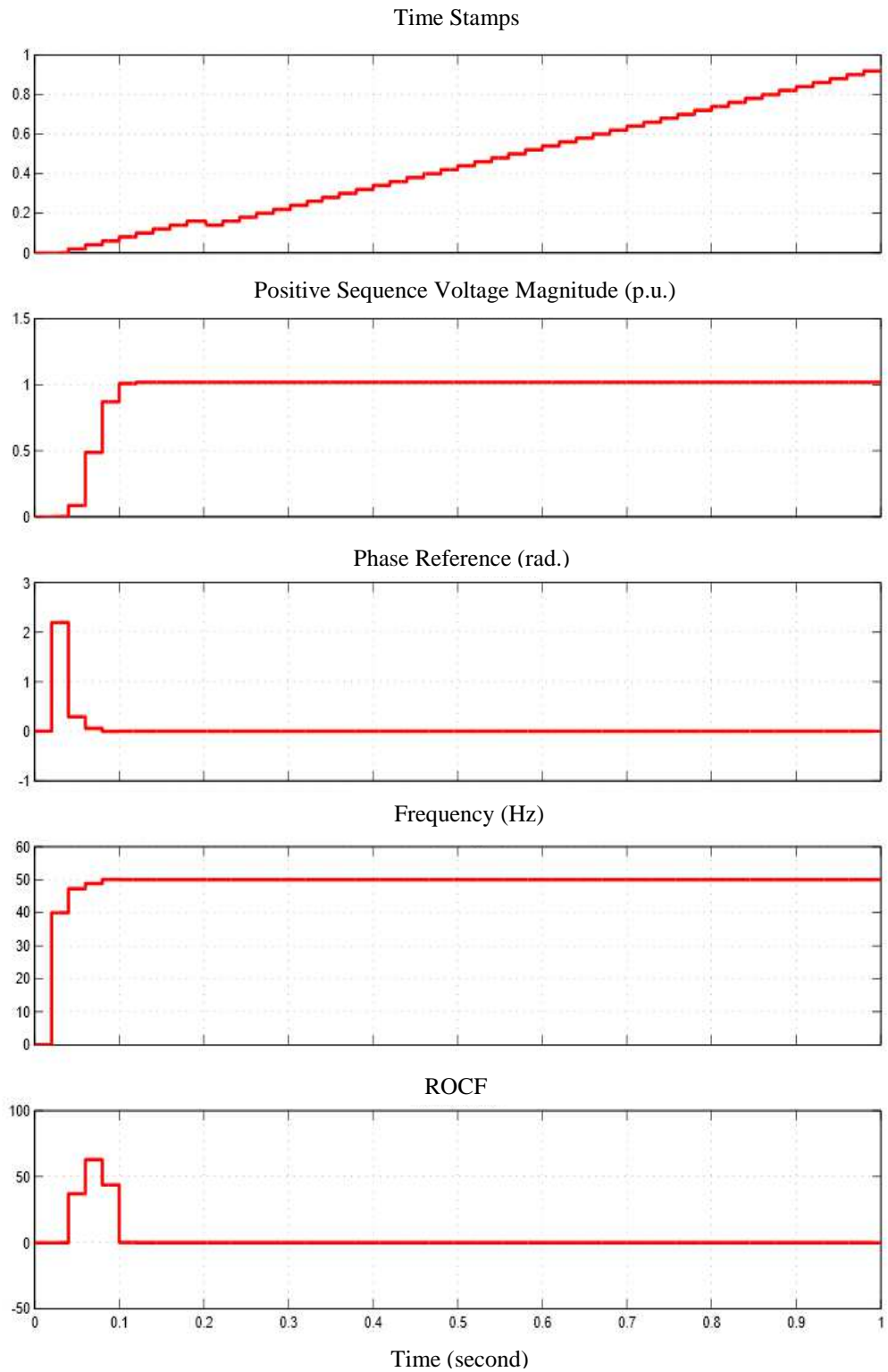


Figure 2.4 : Output results of PMU. Here the applied sample signal parameters are Voltage magnitude: 1.02 p.u., frequency: 50 Hz

3. MATHEMATICAL BACKGROUND

Brief review of mathematical techniques utilized for analysis is given as follows:

3.1 Fourier Transformation

J. Fourier, French mathematician, expressed periodic function as an infinite sum of periodic sines and cosines functions known as Fourier Series. Later the concept was extended to Fourier Transform (for non-periodic signals) and Short Time Fourier Transform (for non-stationary signals). Mathematical background of the same is given in following sections.

3.1.1 Fourier series

Consider a periodic function $p(t)$, its corresponding Fourier Series is given as follows:

$$p(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos k\omega_0 t + b_k \sin k\omega_0 t) \quad (3.1)$$

Where, a_k and b_k are real quantities. Complex representation of the same function $p(t)$ using positive harmonics is written as:

$$p(t) = C_0 + \sum_{k=1}^{\infty} C_k \cos(\omega_0 t + \theta_k) \quad (3.2)$$

Where, $C_k = \sqrt{a_k^2 + b_k^2}$ & $\theta_k = \tan^{-1}\left(\frac{-b_k}{a_k}\right)$. C_k can be represented in phasor form as follows:

$$C_k = |C_k| e^{j\theta_k} \quad (3.3)$$

Where, $|C_k|$ is the magnitude and θ_k is the phase angle. The same has provided the basis for phasor quantities.

3.1.2 Fourier transform

Later his studies were generalized to non-periodic continuous time signals (Fourier Transform) and non-periodic discrete time signals (Discrete Fourier Transform). Consider the same periodic function $p(t)$ in exponential form as given below:

$$p(t) = \sum_{-\infty}^{\infty} \alpha_k e^{jk\omega_0 t} \quad (3.4)$$

Where,

$$\alpha_k = \frac{1}{T} \int_{t_0}^{t_0+T} p(t) e^{-jk\omega_0 t} \quad (3.5)$$

Namely,

$$p(t) = \sum_{-\infty}^{\infty} \left[\frac{1}{T} \int_{-T/2}^{T/2} p(t') e^{-jk\omega_0 t'} \right] e^{jk\omega_0 t} \quad (3.6)$$

Assuming that $\omega_0 = \frac{2\pi}{T}$, while $T \rightarrow \infty$, $\omega_0 \rightarrow d\omega$ & $k\omega_0 \rightarrow \omega$, Equation 3.6 can be written as:

$$p(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \left[\frac{1}{T} \int_{-T/2}^{T/2} p(t') e^{-j\omega t'} . dt' \right] e^{j\omega t} d\omega \quad (3.7)$$

Integral inside the brackets of Equation 3.7 gives the Fourier Transform $\hat{p}(\omega)$ as:

$$\hat{p}(\omega) = \frac{1}{T} \int_{-T/2}^{T/2} p(t') e^{-j\omega t'} . dt' \quad (3.8)$$

Similarly, Inverse Fourier Transform of the $\hat{p}(\omega)$ is also given as:

$$p(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \hat{p}(\omega) e^{j\omega t} d\omega \quad (3.9)$$

These generalizations made possible for adaptation of this powerful mathematical interpretation in computers. Due to large computational requirements, DFT was not widely utilized in computer applications. Later more efficient algorithm, known as Cooley Tukey algorithm, was introduced in 1965 which became more popular in computer related applications [20].

3.1.3 Short time fourier transform

However, above techniques cannot capture the non-stationary changes within the signals. Later this limitation was removed by applying FT on small data sets by sliding the window function over the time axis. While frequency and time resolution are constant for each step because of fixed window function length. This technique was known as short time Fourier Transform (STFT) and was first introduced by Dennis Gabor[21].

General expression for the STFT is given as follows:

$$\hat{p}_\omega(\omega, b) = \int_{-\infty}^{+\infty} p(u) \overline{\omega(u-b)} e^{-j\omega u} du \quad (3.10)$$

Where, $\omega(u - t)$ is the window function and bar on the window function represents conjugation. Fixed resolution of STFT can be shown in following figure:

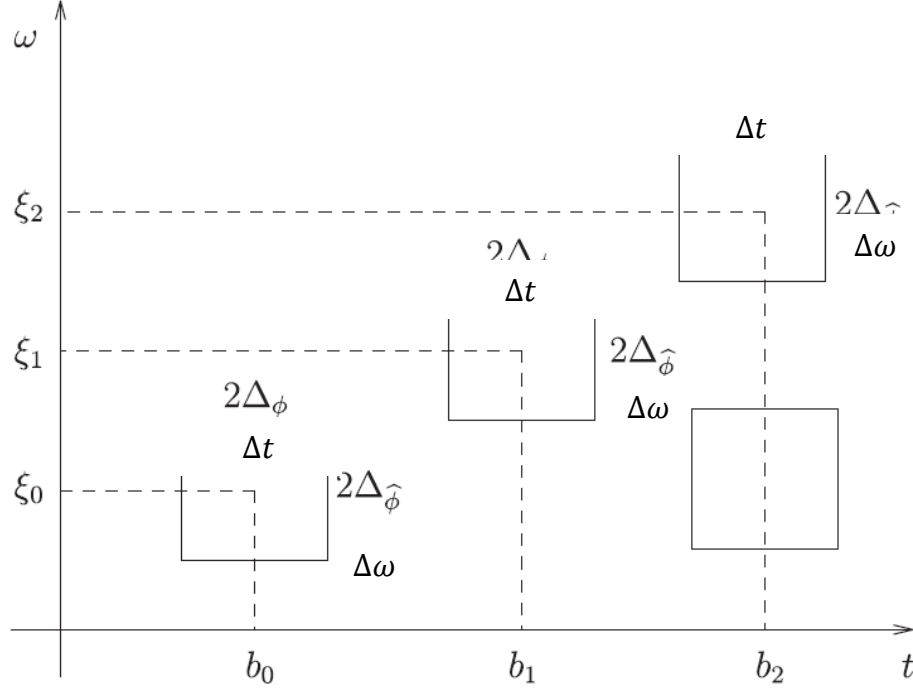


Figure 3.1 : Time Frequency Window for STFT

3.2 Wavelet Transform

Wavelet Transform (WT), being an alternate to STFT, solves resolution related discrepancies by introduction of scaling parameter that gives variable resolution. However, the time and frequency cannot be measured accurately at a given time instant. There is always been a tradeoff between these two values. In other words, it is impossible to calculate the exact spectral component at any given instant of time. At best in a given time interval we can find out the corresponding spectral components. Consider a family of functions: $g_{(a,t)}(u) = \frac{1}{\sqrt{a}} g(\frac{u-t}{a})$. Here we have two parameters to alter. The shifting parameter "t" achieves the sliding feature while parameter "a" alters the width of the window function e.g. shrinking ($a < 1$) or dilating ($a > 1$). General expression for WT is given as:

$$L_g f(a, t) = \int_{-\infty}^{+\infty} f(u) \overline{g_{(a,t)}(u)} du \quad (3.11)$$

The wavelet function, $g_{(a,t)}(u) = \frac{1}{\sqrt{a}} g(\frac{u-t}{a})$ is dilated by parameter "a" and translated by parameter "t" is designed to balance between time domain and frequency domain resolution. In other words, either signal can be accurately found in time or frequency domain but not in both domains. This phenomenon is similar to Heisenberg Uncertainty Principle, introduced first in 1927 by the German physicist Werner

Heisenberg, which states that the more precisely the position of some particle is determined, the less precisely its momentum can be known, and vice versa.

Variable resolution of WT is shown in following figure:

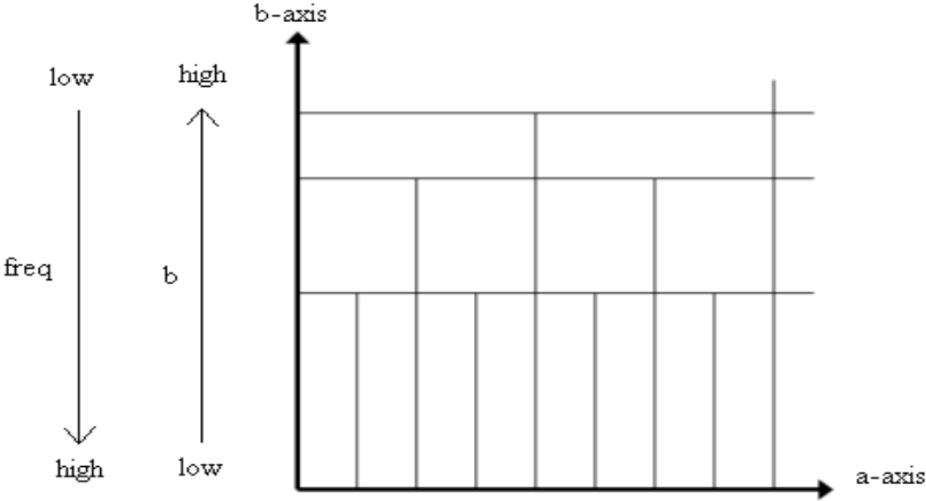


Figure 3.2 : Multi resolution of WT

Here, a-axis is time and b-axis can be either frequency (freq) or scales (b). Arrows designated with “freq” and “b” gives the increasing direction of frequencies and scales, respectively.

Multi resolution of WT as depicted by the Figure 3.2 is achieved by the scaling and shifting of the analyzing function. Consider, an analyzing function i.e. $\psi_{jk}(t) = 2^{j/2}\psi(2^j t - k)$ in time-scale domain using shifting & translation parameter is shown in following figure:

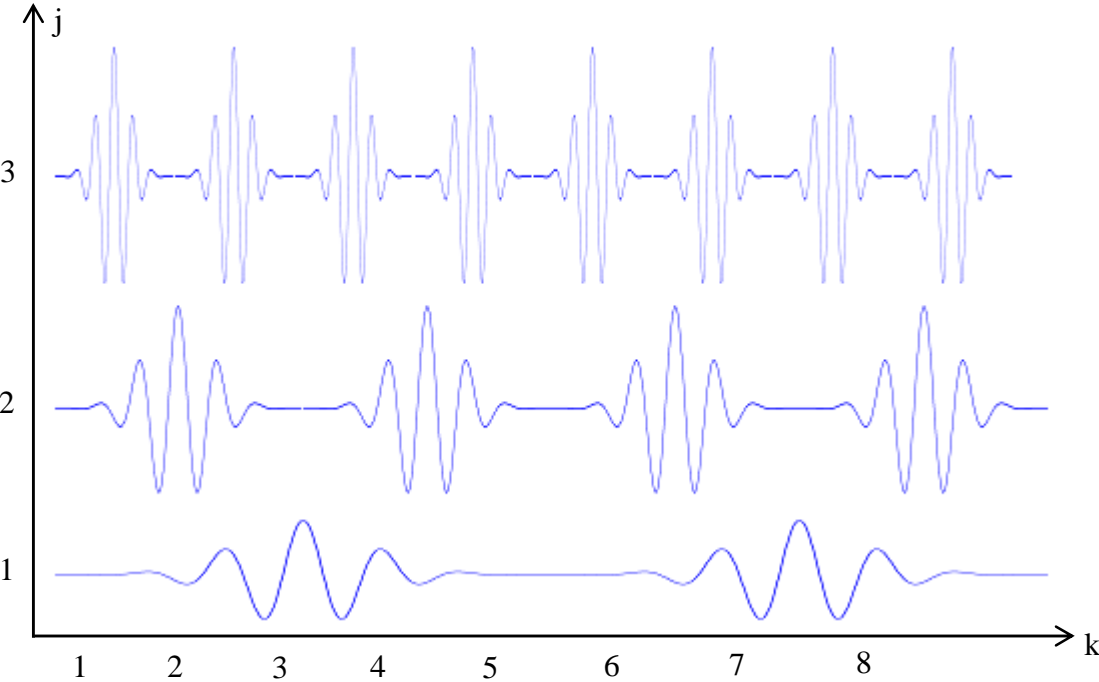


Figure 3.3 : Subband Analysis

3.3 Multi-resolution Analysis

In Multi-resolution Analysis (MRA) we can define space V_{j-1} as follows:

$$V_{j-1} = \overline{\text{span}}_k \{2^{(j+1)/2} \phi(2^{j+1}t - k)\} \quad (3.12)$$

As a result, a given signal $x(t)$ in the V_{j-1} space can be expressed as:

$$x(t) = \sum_k a_{j-1,k} 2^{(j+1)/2} \phi(2^{j+1}t - k) \quad (3.13)$$

If such a signal is projected (i.e., decomposed) onto the V_j and W_j spaces, the result can be expressed as

$$x(t) = \sum_k a_{j,k} 2^{j/2} \phi(2^j t - k) + \sum_k d_{j,k} 2^{j/2} \psi(2^j t - k) \quad (3.14)$$

Ultimately, after further manipulation, the signal $x(t)$, through pairs of filters is decomposed into low- and high-frequency components as follows:

$$\begin{cases} a_{j,k} = \sum_m h(m - 2k) a_{j-1,m} \\ d_{j,k} = \sum_m g(m - 2k) a_{j-1,m} \end{cases} \quad (3.15)$$

In Equation 3.15, $a_{j,k}$ is the approximate coefficient (or low-frequency component of the signal) and $d_{j,k}$ is the detailed coefficient (or high-frequency component). To obtain the subsequent detailed coefficient at the next decomposition level ($j + 1$), detailed coefficient at level j is convolved with low pass filter. Similarly, to obtain the subsequent approximate coefficient at the next decomposition level ($j + 1$), approximate coefficient at level j is convolved with high pass filter. Schematic layout of MRA showing the low- and high-frequency decomposition is given as follows:

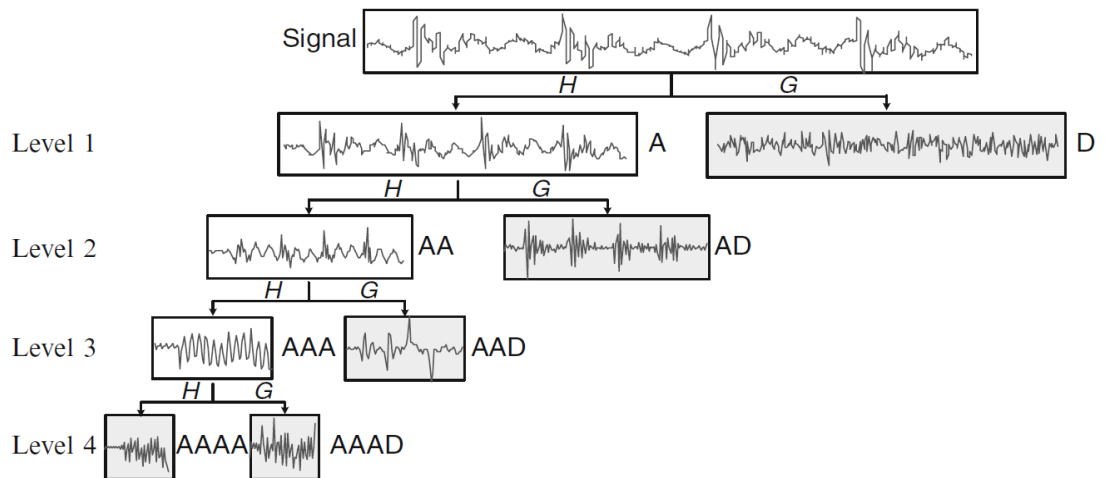


Figure 3.4 : Splitting of signal spectrum using MRA [22].

Here, H is Low Pass Filter, G is High Pass Filter, A is Approximation & D is Detail. Figure 3.4 shows four level decomposition of the given signal.

3.4 Prony Analysis (Prony's Method)

Originally, Gaspard Riche, Baron de Prony in 1795, developed the Prony analysis (PA), while studying the expansion of various gases. But practical applications based on this technique were possible after the advent of digital computers [23]. In his original work, Prony proposed fitting a sum of exponentials to equally spaced data points and extended the model to interpolate at intermediate points. PA is a parametric method that computes amplitude, phase, frequency and damping coefficients of the signal segments. In addition, PA can be considered as system identification method. Nowadays, PA is widely used in power system for detection of electromechanical oscillation, biomedical applications, speech signal processing etc.

For a mathematical expression of PA, consider $y(t)$ a signal consisting of N evenly spaced samples. PA gives the function $\hat{y}(t)$ by directly estimating the parameters by fitting a sum of complex damped sinusoids to equally spaced data points in time, as given below:

$$\hat{y}(t) = \sum_{i=1}^L A_i e^{(\sigma_i t)} \cos(2\pi f_i t + \phi_i) \quad (3.16)$$

Where, A_i is amplitude, σ_i is damping coefficient, ϕ_i is phase and f_i is frequency of component i , respectively. And, L provides the total number of damped exponential components.

4. APPLICATIONS OF PHASOR MEASUREMENT UNITS IN ELECTRICAL POWER SYSTEM

Simulations were done in Simulink Matlab. Two main topics i.e. inter-area oscillations & ferroresonance, were dealt thoroughly to understand their behaviors utilizing measurement based analysis techniques of signal processing.

4.1 Case Study 1: Detection of Inter-area Oscillations

Electromechanical oscillations have been a topic of interest for researchers since many years. Characteristic features of these oscillations can be obtained in time domain as phase & amplitude and in frequency domain as modal frequency and damping. These oscillations, along with causing instability, also limit the capacity of transmitted power due to insufficient damping because of remote generation setups. Generally, power system stabilizers are used to counter the condition of insufficient damping. Power system stabilizers controls generator output by changing the set point of the voltage regulator. Traditionally, this close loop feedback control is based on the locally measured signals such shaft rotational speed, real power output and frequency.

Nowadays, performance of these power system stabilizers can be enhanced using the remotely available accurately time stamped information provided by PMUs e.g. voltage magnitude, voltage phase angle, frequency. This synchronized measured data is generally characterized in appropriate time frame as per requirement of damping control. Hence, it provides a flexible environment in which data can be measured at any desired point/node in the power system and communicated to the several control stations for different objective such as energy management, damping control, isolation of different regions in case of instability and much more.

In WAMS reliable detection and monitoring of power system oscillations is one of the most critical application. So that a valuable information of increasing oscillations and instability be provided to the system operators and detection algorithms. Therefore, that operator is alerted to observe and monitor the synchronized phasor measurements to find the root cause of instability by comparing the data and events occurred during the same time instants. Also corrective actions can be taken to safe guard the further instability [24, 25]. One important consideration here is, for the appropriate and reliable data, to optimally allocate PMUs to meet the observability and controllability conditions for the power system control aspects. For example modal analyses were used as a basis for the optimum allocation of PMUs in the power system [25].

Extraction of features of interarea oscillations using signal processing techniques is more convenient than the conventional model analysis method using eigenvalues

analysis for a specific system configuration [24]. Although one such application based on model based approach has been developed for WAMS. Through this approach optimal model parameters were identified by applying autoregressive model and Kalman Filtering techniques using data measured from carefully allocated PMUs [25]. Traditionally model analysis is used for detection of modes of the oscillations [26]. With the current encouraging deployment trend of PMUs, oscillations can be measured in real time due to high-resolution measured data. Post disturbance analysis along with the estimation of system qualitative parameters such as eigenvalues as described by Liu and Venkatasubramanian can be measured [27].

4.1.1 Simulation environment & model

Two machines model is considered for the analysis as show in Figure 4.1.

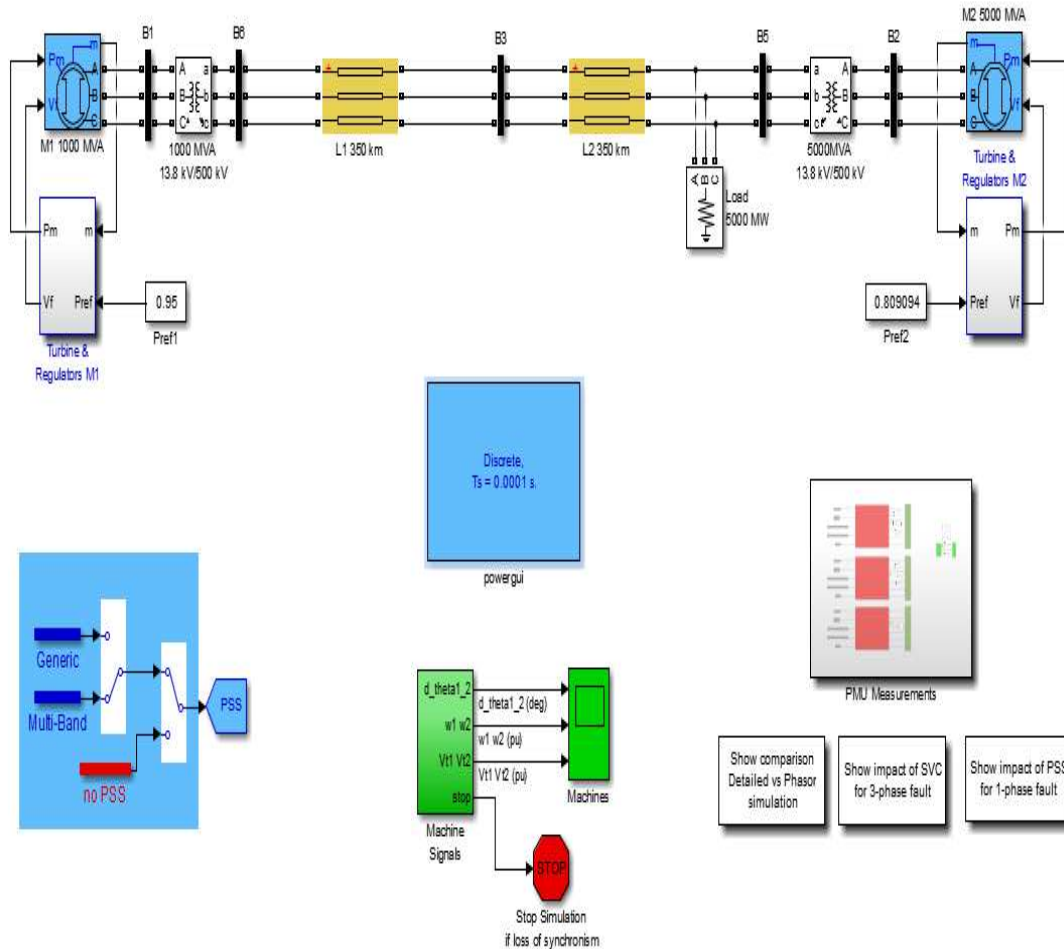


Figure 4.1 : Two machines model in Matlab Simulink

4.1.2 Analysis method & objective

Machines stability analysis was carried out using the outputs obtained through the Simulink-PMU model installed at the respective buses of machines. Events and their features extractions were analyzed using the spectral measuring techniques in time, frequency and time-frequency domains e.g. Short Time Fourier Transform, Continuous Wavelet Transforms etc. Furthermore Prony analysis was applied on the acquired signals for identification of oscillation properties i.e. mode frequency, mode damping, and mode shape. Scenarios were created by applying faults, load changes

while keeping power system stabilizer (PSS) on different setting. And impacts of all scenarios were investigated using the foresaid analysis techniques.

4.1.3 De-noising and filtration of the signal

As signal obtained from the output of the Simulink PMU model generates a noisy signal due to dynamic behavior during the transient conditions. Also we are interested in extraction of low frequency signals (generally inter-area oscillations lies within the range of 0.2 to 1 Hz). To achieve both objectives of de-noising and filtration, Mallet Algorithm [28] based on Multi-resolution Analysis (MRA) is used.

An example for de-noising and filtering of the given signal to obtain the detail coefficient taken from one of the simulation scenarios (based on load variation) obtained at the decomposition level $j=9$ is given in Figure 4.2:

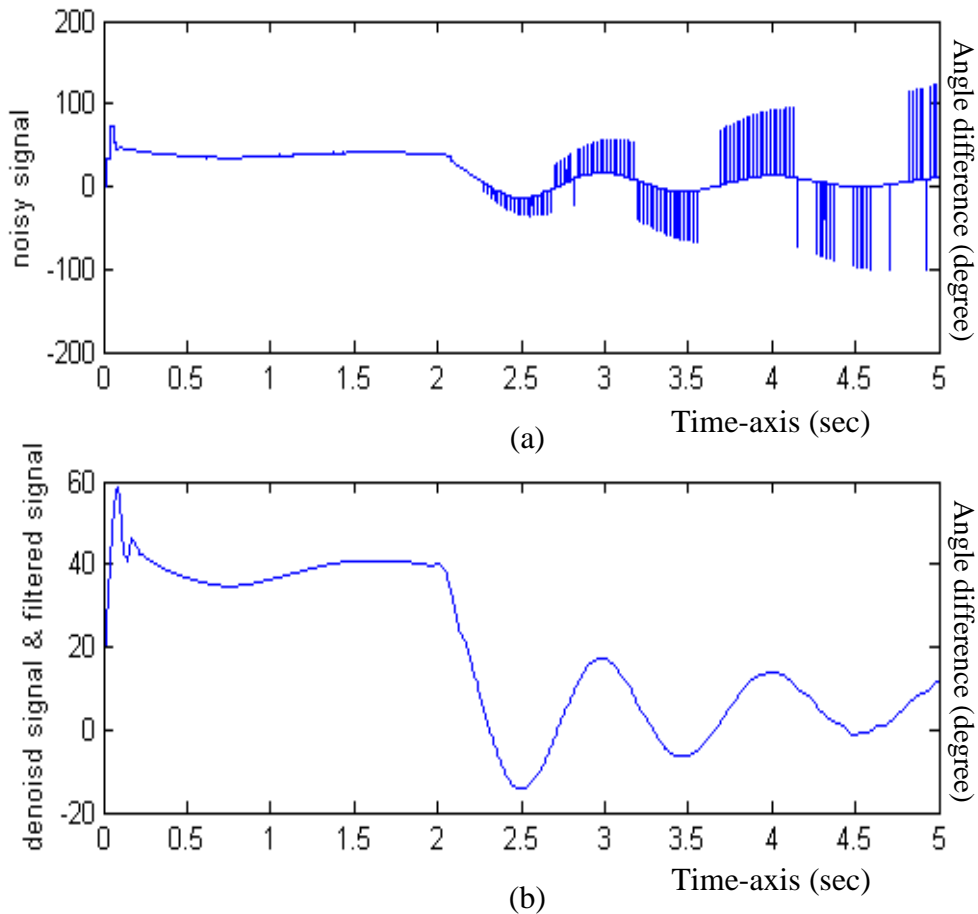


Figure 4.2 : De-noising and filtration of signal (a): Noisy signal, (b): Filtered Signal

4.1.4 Simulation scenarios

Simulations were carried out based on the different modes of the power system stabilizer (PSS) setting, faults and load changes. And impacts of all scenarios were investigated using the foresaid signal analysis techniques. However, for the matter of conciseness and limitation of space following two scenarios are given in detail with results and graphs:

- Scenario I: Based on load variation having PSS set at “Generic Mode”

- Scenario II: Based on 2-phase fault having “No PSS”

4.1.4.1 Scenario I: Based on load variation having PSS set at “Generic Mode”

Complete static load of 500MW was disconnected suddenly at 2 sec while keeping power system stabilizer (PSS) in the “Generic” position. PSS successfully damped the oscillations and machines connected to Bus-1&2 remained in their stability limits as shown in Figure 4.3. An important phenomenon observed was that the angle-difference measured by PMU block installed at Bus-1&2 is almost same as the difference of internal angle of machines connected to the Bus1&2 respectively, which is shown below:

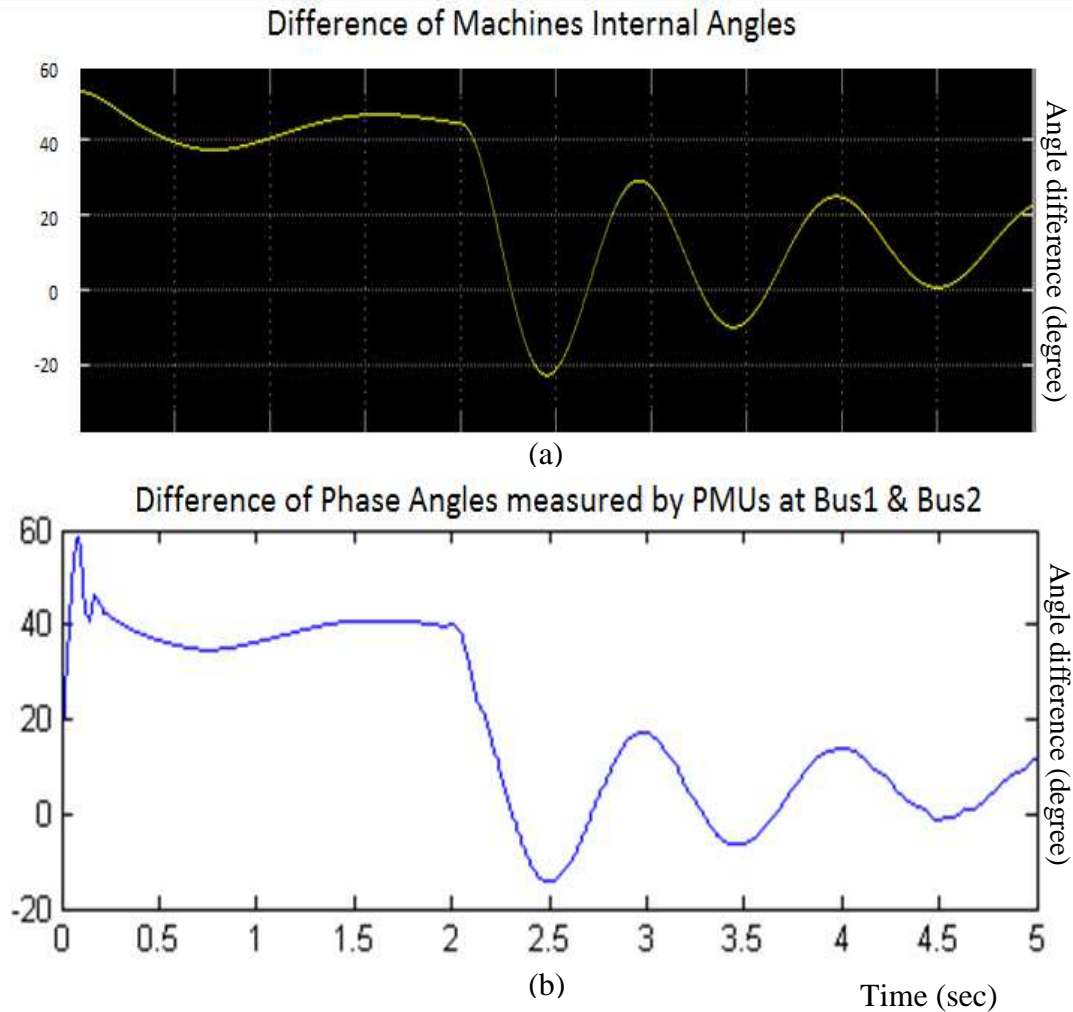


Figure 4.3 : Comparison of measured angle difference of (a): Machines internal angles connected to Bus-1&2, (b) PMUs installed at Bus-1&2

Hence, PMU installed at Machine-connected buses gives an insight into the angle stability of the machines because rotor angle inherently captures the nonlinear and non-stationary dynamics of the system and can be used to determine linear and nonlinear attributes of system oscillations. This provides a basis for online stability analysis of the machine connected to the respective bus, which was impossible in previous SCADA system because of low resolution.

Prony analysis using Prony-Toolbox [29] is applied on different segments (based on time) of the de-noised and filtered signal of angle difference measured by PMU

block installed at Bus-1&2. And it is observed that inter-area oscillation (0.2-1 Hz) modes are successfully damped by the PSS. In addition, local modes (generally in the range 1-2 Hz) i.e. at 1.1 Hz are observed b/w time 2-5 seconds were also damped out. Results are given in following Table 4.1:

Table 4.1 : Prony Analysis of scenario I

Time Segments (Sec)	Results				
	Mode	Amplitude	Damping	Frequency	Energy
1.5 – 1.9	1	82	-0.31	0	5.7×10^6
	2	0.004	-91	0	2.3×10^{-4}
	3	0.0032	-2.2	0	4.7×10^{-3}
2 – 2.5	1	49	-4	1.1	7.2×10^5
	2	49	-4	1.1	7.2×10^5
	3	0.0064	-130	0	4.2×10^{-4}
3.9 – 4.4	1	26	-4.6	0	1.8×10^5
	2	0.085	-100	0	9.0×10^{-2}
	3	0.019	-4.6	0.51	9.0×10^{-2}

Short time Fourier Transform of the same is given as following Figure 4.4:

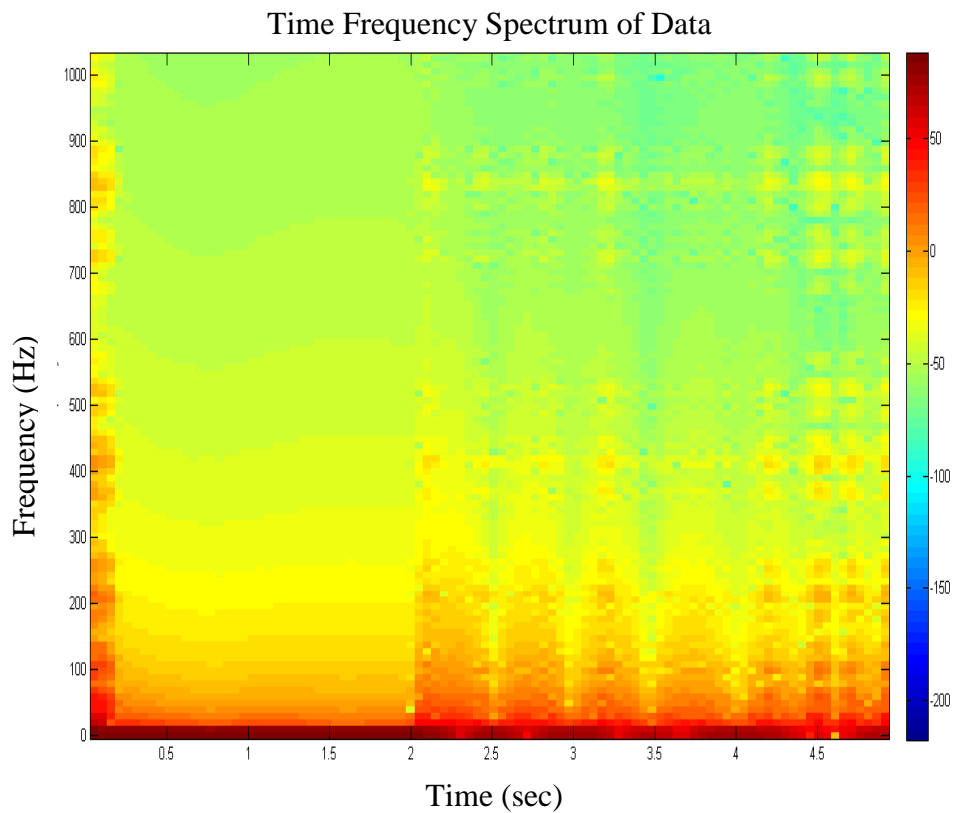


Figure 4.4 : STFT of the analyzed signal

Zoomed view of STFT of the above figure 4.4 by highlighting the low frequencies components is given as following figure 4.5:

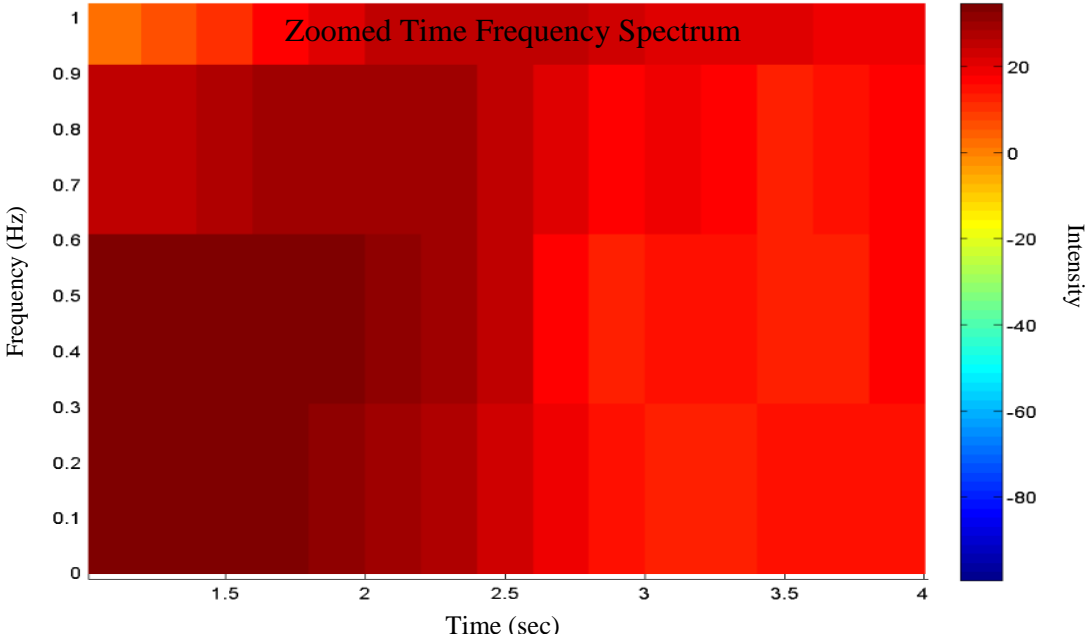


Figure 4.5 : Zoomed STFT of the analyzed signal

Also, the continuous wavelet transform the same signal highlighting more features is given in Figure 4.6. It gives more insight by highlighting the low frequency components, which can be clearly seen during different time intervals after 2 sec when disturbance was applied. Low frequency components can easily be seen at high scale values with their intensity basing on color (e.g. blue color as highest intensity while red color is showing lowest intensity). In addition, it can be observed that low frequency components present at time interval 2 sec to 2.5 are successfully damped by the PSS. Hence, it provides a visual add for the operators to observe low frequency components and their intensities during given interval and can take appropriate action.

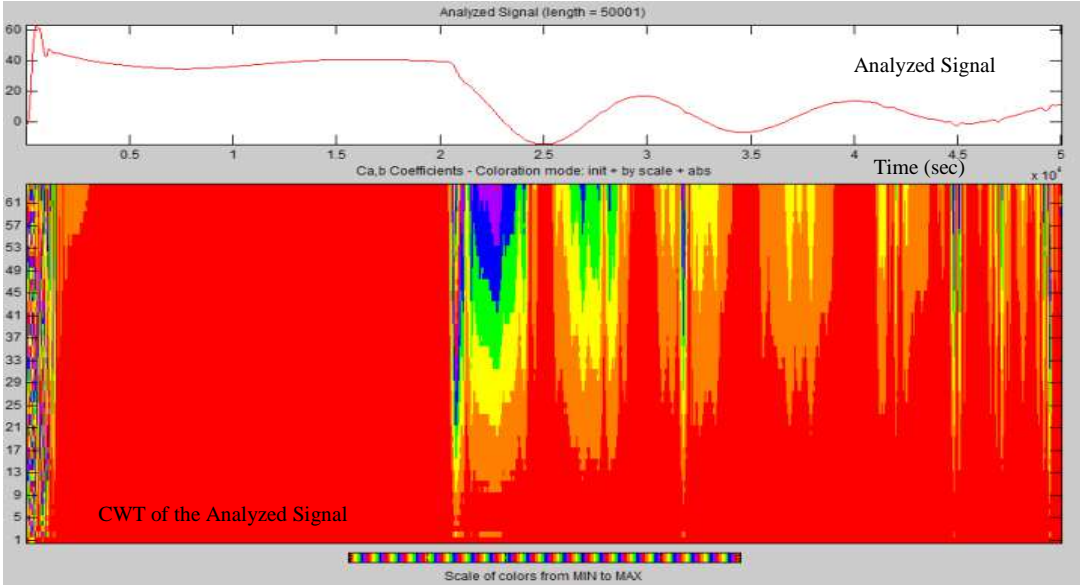


Figure 4.6 : Continuous Wavelet Transform of the analyzed signal

4.1.4.2 Scenario II: Based on 2-phase fault “Without PSS”

Two-phase fault was generated at the output of the Transformer (1000MVA) output bus (Bus-6) at 2 sec while keeping power system stabilizer (PSS) at the “No PSS” position. Angle stability of the machines was not achieved as angle difference is getting larger and larger. Output signal of the angle difference measured by the PMUs installed at Bus-1&2 is shown in Figure 4.7.

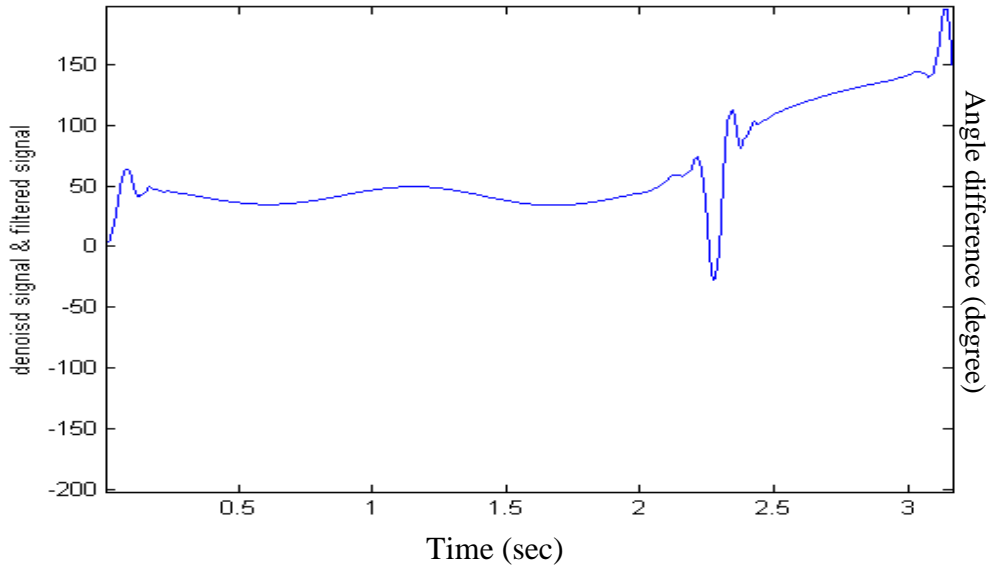


Figure 4.7 : Angle difference measured from PMUs installed at Bus-1&2.

Prony analysis results showed the presence of the dominant inter-area oscillation mode at 0.29 Hz having the largest energy in the signal (as shown in Table 4.2) before the fault and the same resulted in the instability of the machines when 2-phase fault was applied at time 2 seconds for next 12 cycles during the simulation. Results of the same are given in Table 4.2.

Table 4.2 : Prony Analysis of scenario II

Time Segments (Sec)	Results				
	Mode	Amplitude	Damping	Frequency	Energy
0.9 – 1.4	1	79	+0.46	0.29	1.2×10^7
	2	0.047	-88	0	3.1×10^{-2}
	3	0.015	+0.46	0.29	4.3×10^{-1}
	4	0.000056	-1800	320	2.6×10^{-9}

4.1.5 Conclusion

During this study, a simulation environment based on Simulink model of PMU was built and successfully feature extraction of the signals was achieved. This provides a virtual environment to test and analyze the power system using measurement based system from the retrieved information of PMUs. Observation of the similar behavior

of the difference of internal angle of machines and difference of angle measured from the PMU connected to the relevant buses was quite interesting as it provided the basis to extract useful information.

In future these analyzed results can be made basis to categorize these signals e.g. into steady-state (normal operation) and transient (in case of disturbances) conditions. Furthermore, features can be extracted from the categorized signal, which can be used in machine learning algorithms so that online automatic detection of these scenarios can be achieved. Utilization of this information in damping control can be an effective method of improving the performance of the power system, particularly for inter-area oscillations i.e. by using the PMU to identify frequency oscillations and initiate damping activities. And when inter-area oscillations are unstable, the interconnected network can be broken up, potentially leading to islanding.

4.2 Case Study 2: Detection of Ferroresonance Phenomenon in Electrical Power System

This study involves the application of the Simulink model of Phasor Measurement Unit (PMU) based on algorithm from C37.118.1 for the detection of ferroresonance phenomenon for the Seyitomer–Isiklar part of the Electric Power System of 380 kV in Turkey using signal analysis techniques in time, frequency and time-frequency domains. The findings show that the ferroresonance event can be represented by the interharmonics between 50 and 250 Hz. These analysis techniques will result in better monitoring, identification and helps to take prevention measures to avoid undesirable condition in the power system operation.

4.2.1 Ferroresonance

The ferroresonance phenomenon is one of the critical problems occurring in electrical power systems. In ferroresonance condition over-voltages are observed in the power system. Ferroresonance phenomenon is generally nonlinear in nature. The ferroresonance phenomenon generally occurs due to unbalanced condition such as switching, the serial connections of the capacitors with transformer magnetizing impedance etc. These over voltages cause failures in transformers, cables, and arresters. The ferroresonance phenomenon is more prominent at high voltage levels because the relative ratios of losses, magnetizing impedance and cable capacitance lies in favorable ranges here [30, 31].

4.2.2 Interharmonics

Harmonic problems are very prevalent problems in power systems. In this context, harmonics are usually classified as odd harmonics and even harmonics. Thus, physical events can be categorized according to the harmonics type. For example, in power system applications, odd harmonics are more important than even ones. However, in some events, such as unsymmetrical phases, even harmonics also gain importance due to the properties of the odd harmonics of the system. With the exception of these types of the harmonics, another type of harmonics is sub-harmonics, which are seen at below the fundamental frequency. In addition, the

interharmonics can be defined by the fractions between the integers of the even and odd harmonics. They are obtained through the ferroresonance phenomena. For this reason, the interharmonics are used as an important indicator in the detection of the ferroresonance phenomena. The interharmonics are generated with the inter-modulation of the fundamental and harmonic components of the related system. Hence, they can be observed, since they are proportional with the increase in the load numbers.

4.2.3 Simulation environment

In this study, the ferroresonance phenomenon is introduced for Seyitomer–Isiklar part of the Electric Power System of 380 kV in Turkey. Simulink model of the system is given in Figure 4.8.

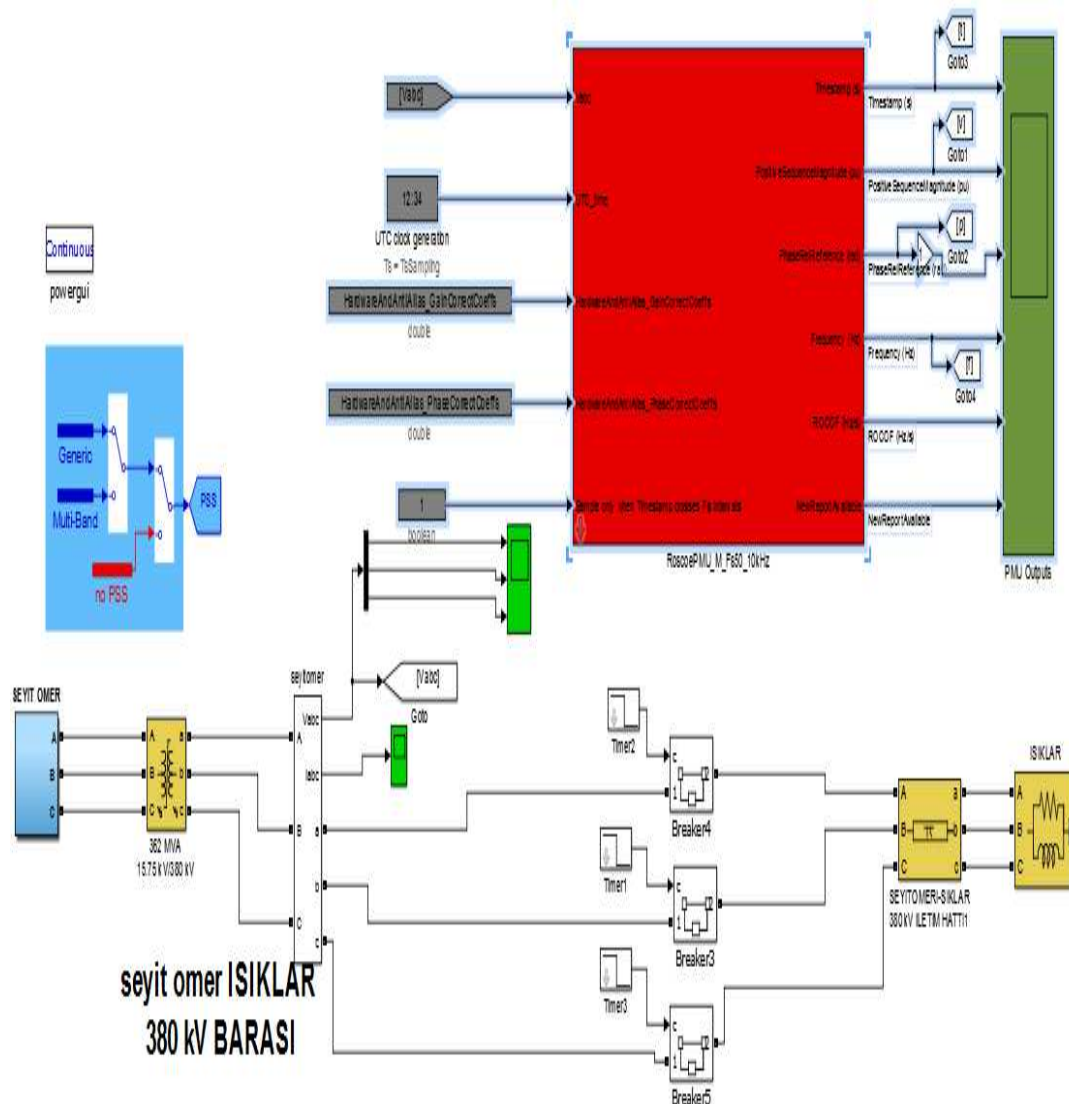


Figure 4.8 : Two machines model in Matlab Simulink

Voltage Signal of the phase-R was given as the input the Phasor Measurement Unit (PMU). All the analyses were made on the re-constructed voltage signal calculated from the information obtained i.e. magnitude, phase and frequency from the PMU. Hence, it provides a methodology to for the remote detection of the different abnormalities including the ferroresonance phenomenon in the power system.

4.2.4 Time domain signal characteristics

Using the Matlab–Simulink model that is defined in Figure 4.8, voltage of phase-R is shown for 4-s duration as shown in Figure 4.9. Here, after the 2nd second, the ferroresonance effect begins to appear.

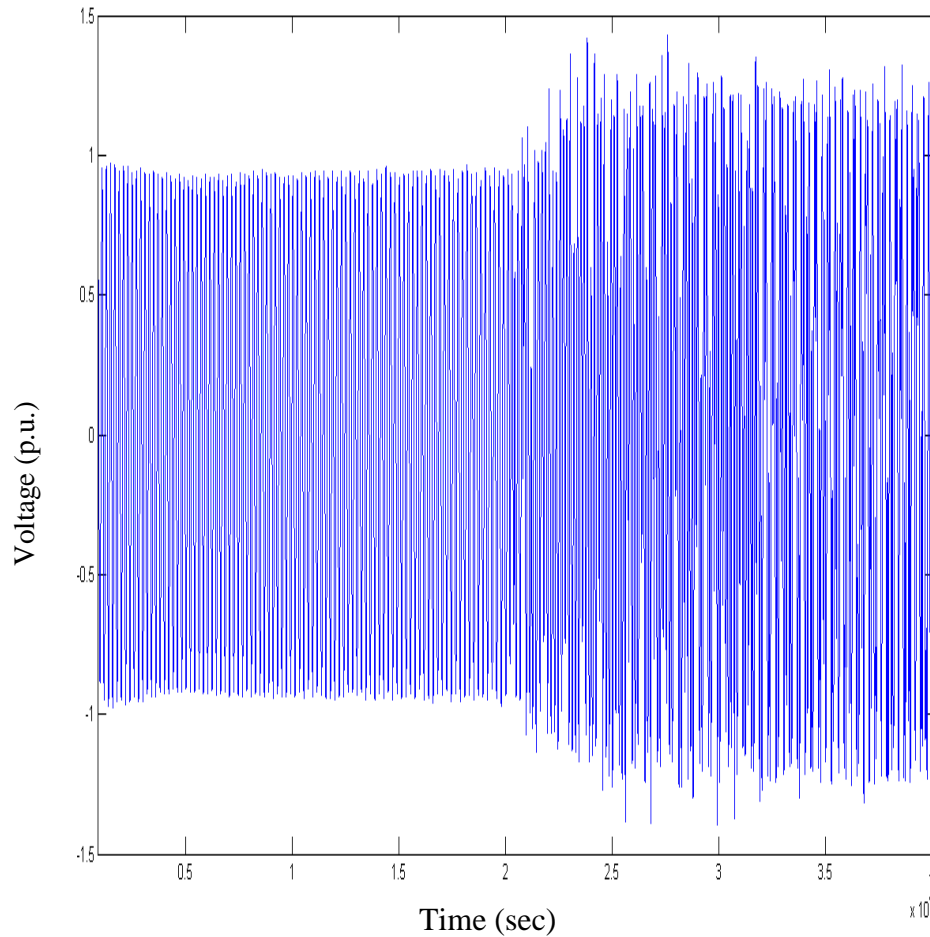


Figure 4.9 : Voltage variation in Phase-R

4.2.5 De-noising and filtration of the signal

As signal obtained from the output of the Simulink PMU model generates a noisy signal due to dynamic behavior during the transient conditions. In addition, we are interested in extraction of low frequency signals (generally within the range of 0 to 250 Hz). To achieve both objectives of de-noising and filtration, Mallet Algorithm [28] based on Multi-resolution Analysis (MRA) is used.

An example for de-noising and filtering a portion of the signal after ferroresonance the obtained at the level $j=3$ is given as shown in Figure 4.10. Here, de-noising technique successfully removed the sharp edges of the noisy signals obtained from PMU. A small segment of the noisy and corresponding filtered signal is shown the Figure 4.10 below:

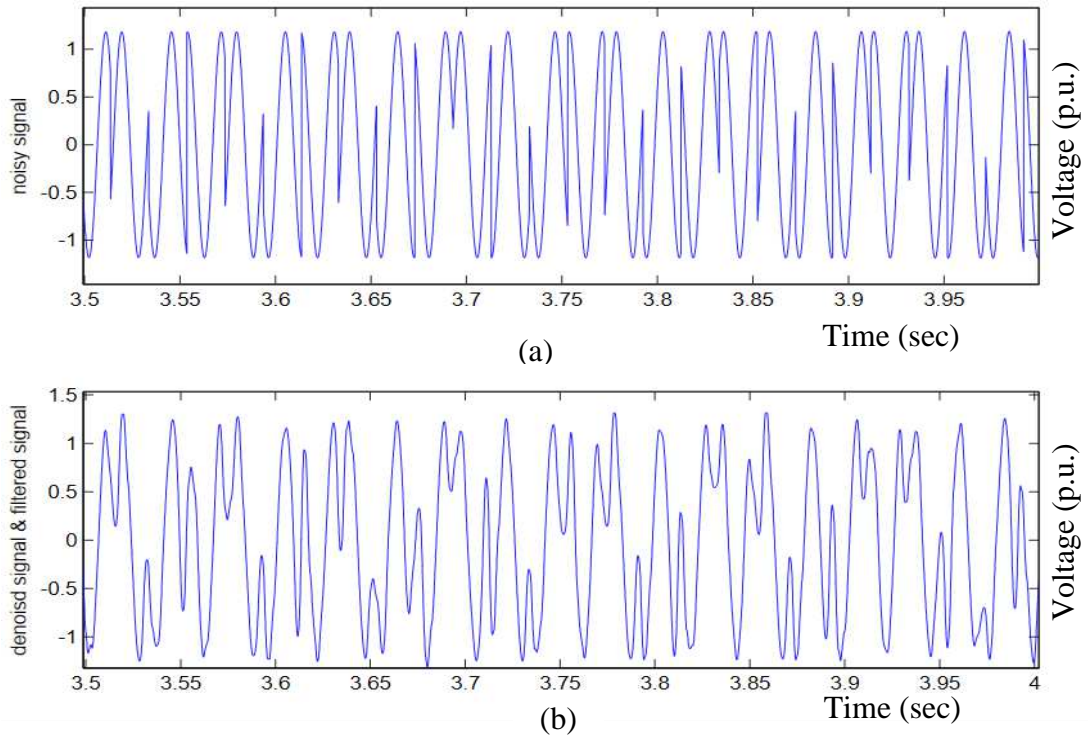


Figure 4.10 : De-noising and filtration of signal (a): Noisy signal, (b): Filtered Signal

4.2.6 Frequency domain signal characteristics

Time domain signal characteristic just give the general trend of the signal but not quite informative to perform parametric identification. For the same the FFT of the phase-R was calculated and which clearly depicted the inter harmonics in the ferroresonance frequency range i.e. 50 – 250 Hz as show in Figure 4.11.

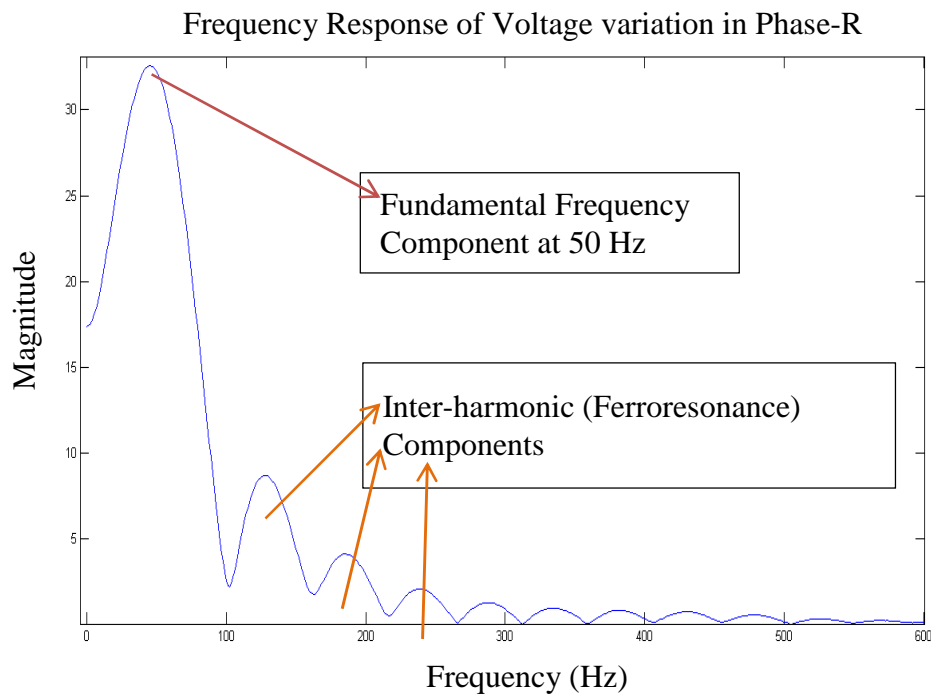


Figure 4.11 : FFT of Voltage variation in Phase-R

As indicated in Figure 4.11, between 0 and 600 Hz, the dominant frequency component is at the 50-Hz level, which is the fundamental frequency of the system. And small amplitudes of the frequencies, which occur between 50 and 250, may be defined as an indicator of the ferroresonance effect.

4.2.7 Time-frequency domain signal characteristics

Short time Fourier Transform (STFT) of phase-R is given in of the Figure 4.12.

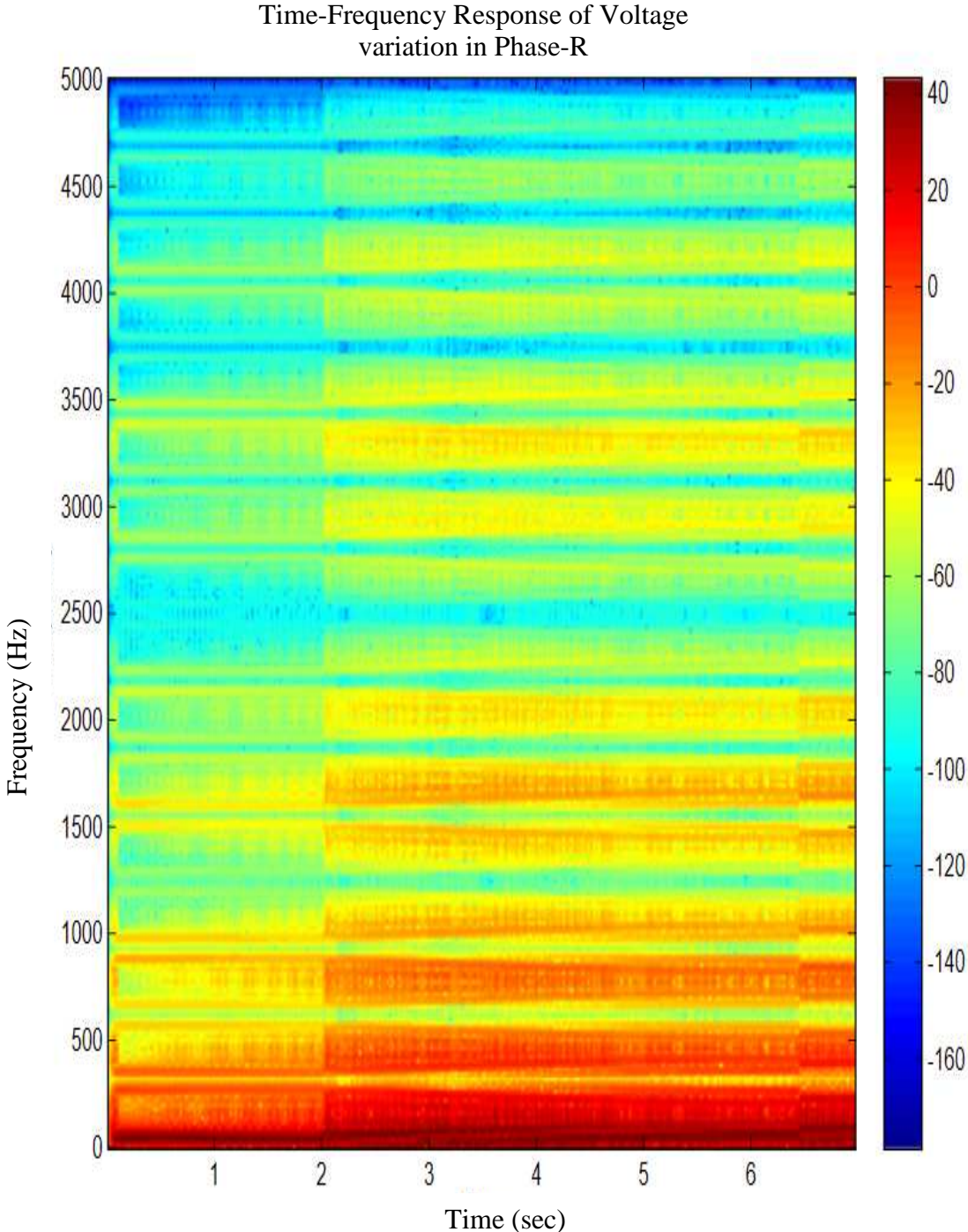


Figure 4.12 : STFT of Voltage variation in Phase-R

As seen in Figure 4.12, according to the sampling frequency of 13 kHz, a time–frequency plane can be shown. Here the fundamental frequency at 50Hz covers the entire time axis; however, after the 2nd second, the ferroresonance effect appears with additional frequencies.

4.2.8 Continuous wavelet transform signal characteristics

Continuous Wavelet Transform of phase-R is given in of the Figure 4.13.

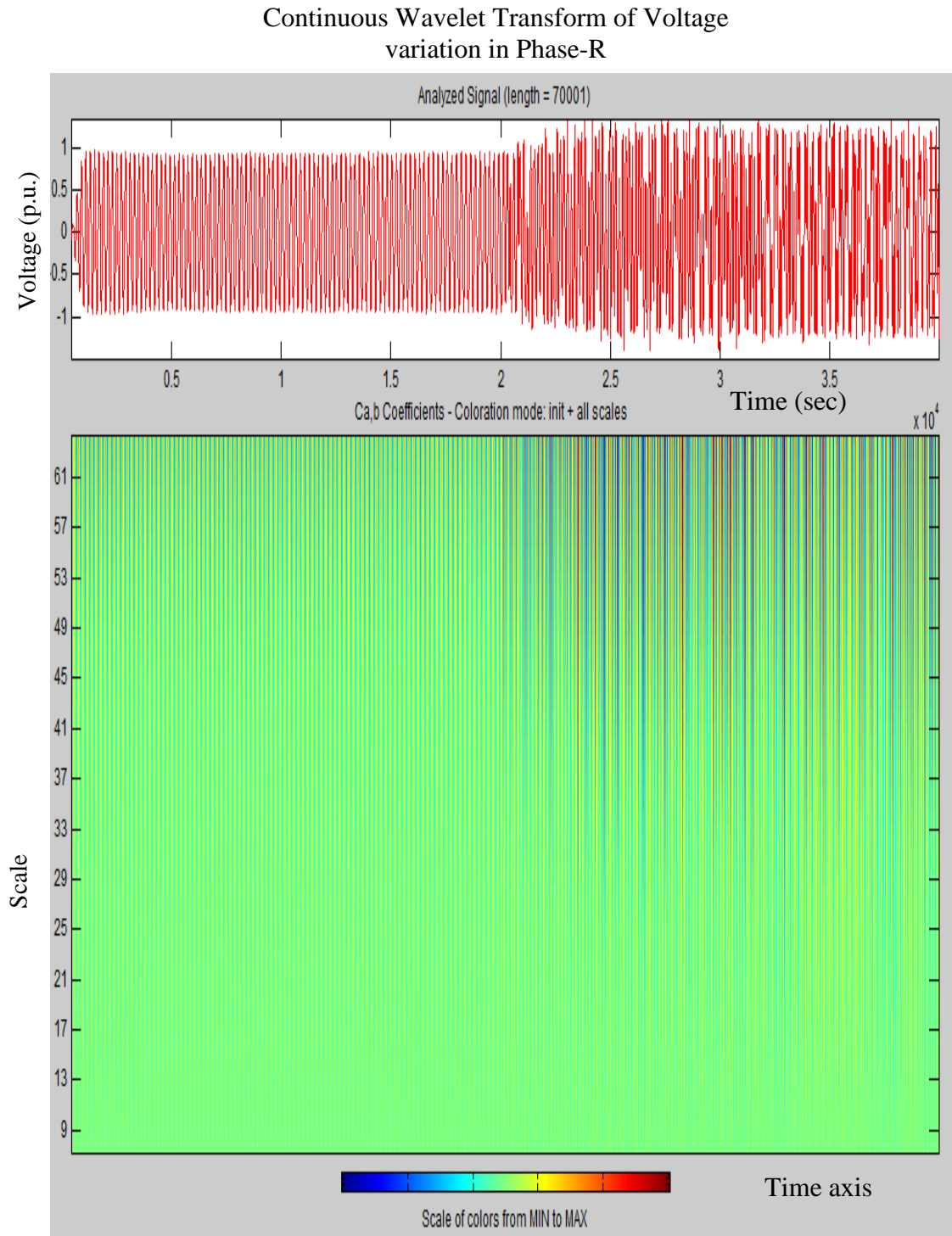


Figure 4.13 : CWT of Voltage variation in Phase-R

4.2.9 Conclusion and future recommendations

During this study, a simulation environment based on Simulink model of PMU was built and successfully feature extraction of the signals was achieved. This provides a virtual environment to test and analyze the power system using measurement based system from the retrieved information of PMUs. Observation of the similar behavior of the reconstructed signal obtained from the PMU connected to the relevant phase and provision of valuable information for detection of ferroresonance phenomenon was quite interesting as it provided the basis for remote detection of different power system abnormalities.

In future these analyzed results can be made basis to categorize these signals e.g. into steady state (normal operation) and transient (in case of disturbances) conditions. Furthermore, features can be extracted from the categorized signal, which can be used in machine learning algorithms so that online automatic detection of these scenarios can be achieved. Utilization of this information in stability control can be an effective method of improving the performance of the power system, particularly for ferroresonance phenomenon.

5. DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS

Electrical energy is such a commodity that is served in fraction of the second after it is generated. This system is very big and complicated comprising of a large number of interconnected devices. This poses a great challenge for the operational management of the grid. Although in current SCADA are utilized for the steady state operations but any dynamic situation is normally estimated beforehand by simulating the models of the grid. Since all scenarios can never be predicted, so there are always loop holes which results in blackouts and other unwanted cases. An important thing here to mention is that although there will be of large amount of data exchange and communication in future in power system but main task is how to refine that big data and extraction of useful information from the same.

In above study it has been shown through the simulated scenarios i.e. detection of inter-area oscillations and ferroresonance phenomenon, that PMUs measurements can successfully achieve the desired results. These applications along with other similar one in Wider Area Monitoring System provides the promising future which will ensure better monitoring, control and grid management on the whole. Blackouts can be avoided through the situational awareness provided by the PMUs. Hence, grid can be operated with enhanced reliability.

Further, I would like to recommend the deployment of PMU in Turkish Grid to benefit from these reliable emerging applications of WAMS. Hybrid setup should be built using the conventional SCADAs and PMUs together to gain the trust of system operators. Studies should be carried out in Turkish grid and system operators should be consulted for deployment of PMUs on the all-critical nodes of the system. More robust state estimation techniques should be developed to enhance the dynamic event capturing capability of PMUs. In addition, a research setup should be developed so that real time values can be obtained for further studies on actual system.

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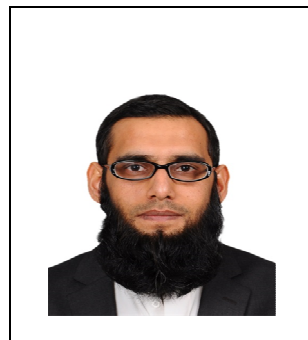
Url-1 <<http://www.hurriyetdailynews.com/expained-how-76-million-people-were-hit-by-turkeys-worst-blackout-since-1999.aspx?pageID=238&nID=80442&NewsCatID=374>>, date retrieved 05.04.2015.

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Submitted Research Articles

- Article-1
 - ✓ Title: Two-Machine Stability Analysis and Inter-Area Oscillation Detection using Simulink Model of Phasor Measurement Unit
 - ✓ Submitted to: IEEE ISGT ASIA 2015 on Innovative Smart Grid Technologies, Bangkok- Thailand
 - ✓ Notification of Acceptance due: 30 June 2015
- Article-2
 - ✓ Title: Detection of Ferroresonance Phenomenon in Electrical Power System using Simulink Model of Phasor Measurement Unit
 - ✓ Submitted : International Conference on Electrical Engineering & Informatics 2015, Bali-Indonesia
 - ✓ Notification of Acceptance due: 08 June 2015

