POWER SYSTEM TRANSIENT FREQUENCY ESTIMATION BASED ON RANDOM FOREST

by

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DEDICATION

"To my respected professors, whose support and guidance have been my guiding lights throughout this academic path."

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POWER SYSTEM TRANSIENT FREQUENCY ESTIMATION BASED ON RANDOM FOREST

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The research is concentrated on “Power Systems Transient Frequency Estimation Based on Random Forest Classifier”. Transient Frequency is a sudden change or abrupt change, within the small duration of the time. A well-known Great Blackout of 2011 in California incident where transient frequency analysis could have been an important study which would prevent the crisis and the blackout event. Transient frequency and Transient events serve as an important aspect for grid operators who can get warning of such events in the early stages from which they can inform their neighborhood utilities or facilities for the crisis prevention and to take the necessary steps.

Grid Stability at 60Hz means the proper operation, proper distribution, prevention of blackout, prevention or managing of overload. If any Fluctuation occurs in the frequency from 60 Hz, it means the system is unsafe and one must disconnect the system in order to be safe which can mainly lead to the power crisis. This Research of study utilizes a machine learning algorithm Random Forest Classifier that boosts up the transient frequency estimation. The initial step involves Generating the signals, applying the threshold-detection method, detecting the transient events, and performing the transient frequency analysis. This will contribute to Signal Processing, Fault Diagnosis, identification of unexpected events, outlier detection, ease the future grid crises, modernization of grid.

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CHAPTER 1: INTRODUCTION

In this century there is an everlasting demand for Electricity, However the concept of stability, reliability and adequacy have been the major concerns. It is required that Electricity Demand must be transmitted and balanced to the consumers by keeping the lights on voltage and Frequency concerns which can lead to stable and reliable power. In order to deliver the demand, the power grid has to anticipate the Transient events and Transient Frequency which are found in very small or short-duration of time and are crucial aspects. If these aspects are left unaddressed there could be the power crisis that can lead to the breakdown of the power supply to uncountable consumers.

It is very important to have real-time monitoring during such activities which can help to mitigate future crises. This study can make some contribution to the world of electricity, with sustainable solutions, innovations and promoting research in the field of power systems engineering.

This study helps to have more resilient and reliable power grids. The thesis "POWER SYSTEM TRANSIENT FREQUENCY ESTIMATION BASED ON RANDOM FOREST CLASSIFIER" helps to look into the machine learning algorithm technique Random Forest Classifier which is supervised learning. With the help of the previous innovations, research and using the machine learning algorithm, the study aims to intensify the veracity of Transient frequency estimation.

Furthermore, in the following pages we look into the Significance, Objective, Generating the signals, looking into the potential of Random Forest Classifier, applying the threshold-detection method, detecting the transient events, and performing the transient frequency analysis. As we explore through the study it becomes evident that transient frequency estimation plays an important role in the world of power systems for the grid's reliability and stability.

Background

Like any electrical system a grid component may fail all of a sudden and is unpredictable. The Large-Scale Great Blackout of 2011 in California that had the chance to be recognized and steps would have been taken to prevent the crisis [3]. This incident gives a clear reminder and challenges to the grid operators. During such events one needs to take the rapid decision by load shedding in which one can disconnect the insignificant load and revive the power generation in order to bring back the grid frequency with stabilization of suitable range. In such cases if the event is unpredictable the transient frequency analysis can be taken into consideration which can give the grid operator early warnings, timely alerts for the transients that can make the grid unstable.

In order to work on the Transient frequency analysis initially the thesis focuses on the standard test signals. The standard test signals are obtained from the reference paper [1],"Evaluating Methods for Measuring Grid Frequency in Low-Inertia Power Systems," In the research paper [1], various frequency measurements methods were followed to reduce the errors in the low-inertia power grids. For more conventional grids with the P-PMU standard, the DFT fit + detector or a well-developed PLL such as the one MATLAB perform well. For low-inertia grids with needs that align with the Rietveld or PSCAD simulated tests, the EKF+corrector method could work if better tuned.

As indicated in Table 1, The Standard Test Signals encompasses wide range the signal of Harmonics Ranging from 2nd - 50th Order, Phase Modulation ranging from frequency 0.1 - 2 Hz, Amplitude Modulation ranging from 0.1 - 2 Hz, and +/- 10 Degree Phase step variations from the research paper [2]. These signals replicate the real-world scenarios or conditions that are come across in power systems to assess the grid stability and reliability.

The study involves generating these signals in MATLAB tool for studying their characteristics, properties and analyzing, employing them in Google Colab with machine learning techniques the study commences.

Table 1: Standard Test Signals

Standard Test Signals	
Signal	**Range**
Harmonics	2nd -50th
Phase Modulation	0.1-2Hz
Amplitude Modulation	0.1-2Hz
+/- 10 Deg Phase Step	+/-10

Previous work overview

In the Research paper [2], the authors address the challenges of the modern power systems. Transient stability was taken as a base function. They used ensemble machine learning algorithm. “The Algorithms XGBOOST and Random Forest Classifier were tested using the test power system IEEE39”.

It was observed that “accuracy of instability classification for XBOOST was found to be around 91.6% and Random forest classifier as 81.6%. The proposed methodology does not apply for Low frequency Oscillation in post-scenario but can be accounted for Dynamic Stability” and wasn’t effective method. Below Figure 1 represents comparison of testing trained algorithms results from the Reference Paper [2].

Parameter	XGBoost	Random Forest
Accounting for power system topology		
Accuracy	0.915	0.816
Average accuracy between classes	0.864	0.744
Precision	0.898	0.847
Recall	0.858	0.851
Not accounting for power system topology		
Accuracy	0.806	0.801
Average accuracy between classes	0.817	0.711
Precision	0.815	0.816
Recall	0.824	0.801

Figure 1: Comparison of testing trained algorithms results

CHAPTER 2: OBJECTIVES

The Objective of the thesis is to identify the Transient events and Transient Frequency analysis with the standard test signals from research paper [1] that are wide range signals and have their own characteristics and behavior. The process involves a well supervised machine learning algorithm "Random Forest Classifier" which plays as a key to detect the transient events. The Standard Test signal encompasses Harmonics Signal (2nd-50th), Phase Modulation (0.1-2Hz), Amplitude Modulation (0.1-2Hz), and +/-10 Deg Phase Step.

Transient events are the main center of the research work. The research employs the "Random Forest Classifier", and Feature extraction is executed to select the amplitude values when a transient event occurs. These are now called the feature vectors that catch the characteristics of the transients and help the examiner to give a clear picture about the transients. As a result, this research not just gives an understanding but also helps to understand the practical aspects too.

Beyond the Technical aspects, the integrated power is always required due to the transients produced. Transient events can include Internal Causes and External Causes like load issues, switch of capacitor banks, tap changings, spikes, faults, disturbances like lightning, poor connections respectively. These can result in partial or total blackout of power systems, causing damage to windings of Generators and Transformers. For Economic reasons it should be taken care to limit and control transient over-voltages. Once the Transient events are detected, Transient events exhibit how stable and soon the signal reaches the steady state under different operating conditions.

CHAPTER 3: LITERATURE REVIEW

Transient frequency analysis is a significant topic in signal processing power systems that deals with the extraction, analysis. Whenever there is trouble in the input signal due to an external cause or internal cause, the output signal which is under steady state with proper operation gets disrupted. To overcome this situation one can, have early warnings and timely alerts by implementing the new technologies. With the advanced technologies like machine learning algorithms that find its various contributions in Data handling, Face/Image recognition, speech recognition, health care and in many more fields and extending its application in the power engineering industry that helps to solve the complexity of power systems operation and control [4].

The Research employs Google Colab platform for signal generation by setting the necessary parameters, Perform the frequency analysis using Fast Fourier Transform (FFT) provided by SciPy the library in python to calculate Discrete Fourier Transform (DFT). Later the Threshold is defined where progressive data values in a trace are recognized point by point [5]. If the value crosses the point whether negative or positive. This threshold determines which peaks to be considered as the transient events. With the DFT computed and threshold defined the transient event peaks are determined. The data points are collected from transient events and data is prepared for machine learning. Features are extracted from the signal that contains the transient events and is used for data preparation. The popular Random Forest Classifier is used to tod the Transient frequency estimation which provides robustness and also involves recognizing the frequency variations associated with transient events. Machine learning models with random forest classifiers are trained to predict the transient frequency depending on the extracted features [6].

Transient Frequency Estimation can help in understanding the signal composition and detecting the transient events in a timely manner. This can ease preventing blackouts, power crises, maintaining the grid stability and modernizing the grids.

Chapter 4: METHODOLOGY

This chapter describes the research methodology. It employs signal processing and machine learning techniques, moves with key steps that consist of Signal Generation process on google colab as the first step followed by Frequency Analysis, Transient event Detection, Data Preparation, Machine learning model Random Forest Classifier application, and Transient frequency estimation. Machine learning models with random forest classifiers are trained to predict the transient frequency depending on the extracted features. By explaining the significance of each step in the process the results are found for Transient event Detection and Transient Frequency Estimation

Figure 2: Steps for Research Methodology

4.1 Platform

Google colab is open source and is a user compatible source that entirely runs on the cloud. It can access the popular python libraries such as Tensorflow, PyTorch, NumPy, Keras, Pandas, SciPy, Matplotlib, Scikit-learn and many more. For our research NumPy is imported for numerical operations, SciPy.fft used to import FFT, SciPy.signal. find_peaks for transient event detection, sklearn.ensemble. Random Forest Classifier for machine learning model, sklearn. model_selection.train_test_split for data splitting, matplotlib.pyplot for plotting [7].

4.2 Signal Generation

Signal Generation is the first process, Signals are nothing but the flow of information or the signal that contains data. Signals needs to be transformed in order to sustain over the channel. Signal processing is the necessary concept. Signal processing can be analog or digital. It uses various techniques like Filtering, Fast Fourier Transform (FFT), Discrete Fourier Transform (DFT), Modulation, Demodulation etc.

This equation helps in generating a sinusoidal signal y(t)=A sin $(2\Pi ft+\boldsymbol{\phi})$, where A= Amplitude of the signal, F =Frequency of signal, $\boldsymbol{\phi}$ =Phase offset of signal, t=time of the signal. To generate the signal initially the parameters are defining mainly the Fundamental Frequency (f0) represent the base oscillation frequency in a periodic waveform, Sampling Frequency (fs) represents number of samples per second, and Duration (T) represents the time of signal. After defining the parameters, we generate the original sinusoidal signal with Fundamental Frequency (f0), with the Duration of time (T) removing all the noise [7].

4.3 Fast -Fourier Transform (FFT)

Fast Fourier Transform (FFT) is a powerful mathematical concept in signal processing which helps in fast computing for training sets. FFT converts time-domain signal to frequency -domain signal and provides the behavior of the signal and allows us to see the signal characteristics of the signal that are not visible and cannot be seen in the time-domain. FFT can help in analyzing a wide range of signals like image, speech, visual, digital filtering, spectral analysis and many more. FFT can help in identifying the amplitudes and the dominant frequencies in the signal which can be used for further or post analysis [8]. In the research Signal is generated and FFT is applied to convert to Frequency-Domain that helps to reveal the amplitude and magnitudes of the signal.

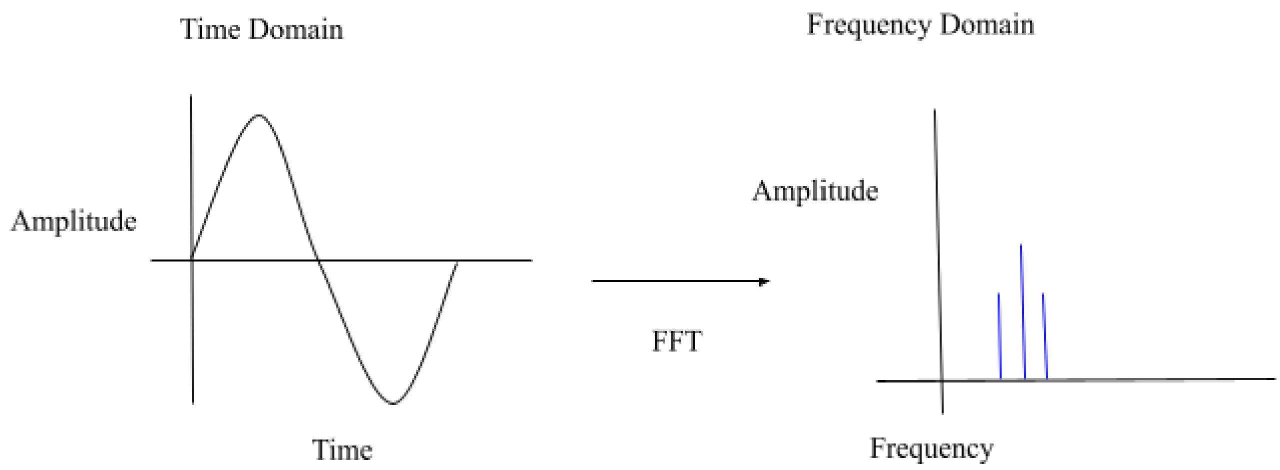

Figure 3: Time Domain and Frequency Domain signal

4.4 Transient Event Detection

In power systems transient events can occur due to various external and internal factors that cause the system to be unstable, and have fatal effects on the equipment and reliability of the power systems [9]. Transient events are short duration of time lived, non-continuous, and create abrupt changes in a line that contains the data in a utility or facility.

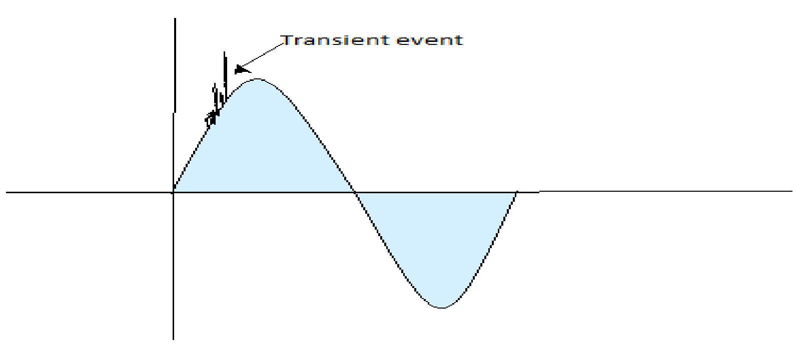

Figure 4: Signal representing the transient event or surges.

They are characterized by high voltages and draw a large amount of current in the electrical system that creates voltage spikes causing the disturbance to entire systems. These can cause Catastrophic failures, Corrupted data or loss of data, tripping off, Short-Circuit [10]. As transient events are short lived it is hard to analyze as they can be missed or not correctly identified due to the fewer samples. It is necessary to detect the transient voltages at high sampling rates to get to know their existence but sometimes metering equipment may not be recognizing the transients because of their short duration and may not be accurate.

In the research transient events are detected by the peaks, threshold is defined where progressive data values in a trace are recognized point by point. If the value crosses the point whether negative or positive the event begins, this threshold determines which peaks to be considered as the transient events. With the DFT computed and threshold defined the transient event peaks are determined.

4.5 Random Forest Classifier

Random Forest is a popular machine learning algorithm. Random Forest model is used both for Classification and Regression algorithms. Random Forest Classifier is a supervised, ensemble learning, providing robustness and accuracy. It consists of a Data Set, further divided into Decision trees, Random Forest classifier it collects the data from all the Decision trees which are subsets to produce the final output with the majority votes as shown in the Figure 5. A function called clf = randomforestclassifier () is called which creates instance and further proceeds to train the classifier using the training data. It combines the ensemble of decision trees during training and combines with predictions to make correct classifications [11].

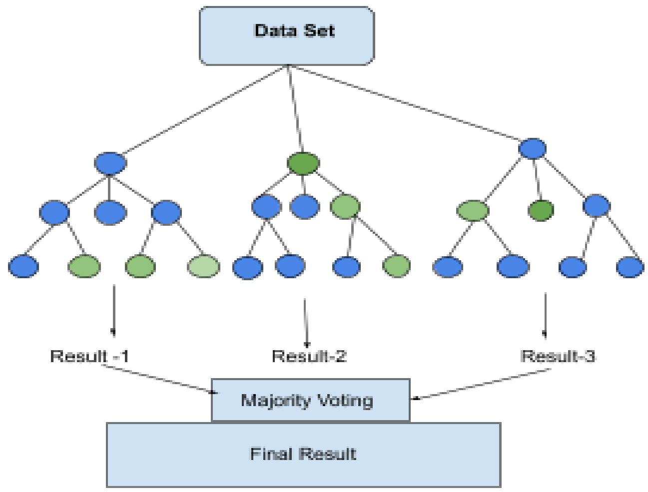

Figure 5: Random Forest Classifier simplified tree.

4.5 Data Preparation and Feature Extraction

Data Processing is a process where the raw data is transformed to make predictions and analysis using machine learning algorithms [12]. In this Research, Data points are grouped from the original signal (f0) by generating a pure sinusoidal wave, with the duration of time (T) along with sampling frequency (Fs). The train_test_split the data is divided as x_train and y_train which are the variables that contain the training data, and x_test and y_test are variables that contain the testing data. Data preparation or processing is done by splitting data into two sets known as Testing sets and Training sets [12]. Here Data points are selected randomly from the grouped data and the rest is used for testing data to check the model performance for accuracy and Reliability. The training data consist of signal data. During the training process the data is passed to the machine to make the predictions, analysis and acknowledge the patterns, here mainly the training model is used to test the data whether the transient events are present in the signal or not. Testing data is used to check the accuracy of the model, to study the model's performance on the data that is not seen.

Feature Extraction is an important process or task that helps to eliminate the unwanted variables and extract the relevant data [13]. This helps to enhance the efficiency of analysis. In machine learning algorithms the features are always addressed as “variables”. It helps transform the raw data to numerical features. Here using the function ‘extract_features’ which takes the technical data of signals that are amplitude and transient event indices. It collects the amplitude of the signal and the point or indices where the transient event occurs. Here x1 and x2 are the extracted features of each signal that are stored in an array. Labels and Features extracted are merged into a single data set [15]. This helps in detecting the accurate transient event detection and classification from data and features.

4.6 Transient Frequency Estimation

Transient frequency estimation is defined as how the frequency of signal changes when a transient event occurs within the short duration of time. In the research the (transient_frequency_feature) function is called to evaluate the transient frequency. The Transient Frequency is calculated as a derivative of phase signal with the time represented $\omega(t) = d(t)/dt$. This represents how the frequency of the signal changes over time during the transients. In the study, the data set consists of x as a feature using the amplitude and frequency information and y as labels where each element indicates a transient event if present (1) , if not (0). The transient event points are used as time pointers which are helpful to analyze the signal during the transient event to know how the frequency changes. A function is called Transient_Frequency =np.fft (np.unwrap (np.angle (np.fft.fft(y)))), and np.fft.fft (y) represents the calculation of Discrete Fourier Transform of the output signal, then the phase extraction takes place using np.angle the phase information is extracted from the complex argument passed to it, that contains the information of the phase of each frequency component in the signal, using np.unwrap [16]. This function helps to unwrap the array into a new set of components by transforming deltas to 2π values, then calculating the difference between consecutive elements of the unwrapped phase values, the difference operation calculated is the rate of change of phase with respect to time this helps to estimate the transient frequency. The plots are generated as a subplot to show how the frequency changes over the time during the transient events. Transient Frequency analysis is important for stability of the power systems, for the quality of electricity, protecting the grids, Regulatory Compliance

Chapter 5: Results and Findings

5.1 Harmonic Signals (2nd -50th)

Harmonic Signal is a sinusoidal wave which is associated with the frequency and that is the positive integral multiple of the fundamental frequency [18]. In this study standard test signal of Harmonic Signal ranges from 2nd -50th which are the integers from 2 through 50. The Harmonic signal is generated with amplitude changes and are summed together to obtain the final signal. Once the code is executed, the plots are generated for original Signal with f=60 Hz that represents a sinusoidal wave, harmonic signal with the transient events is plotted as second plot, frequency signal that shows the frequency components of the signal and finally transient frequency signal represents how the signal changes over the time when the transient -event occurs [19]. These signals help to visualize how the signal changes with frequency over the time and about the signal composition.

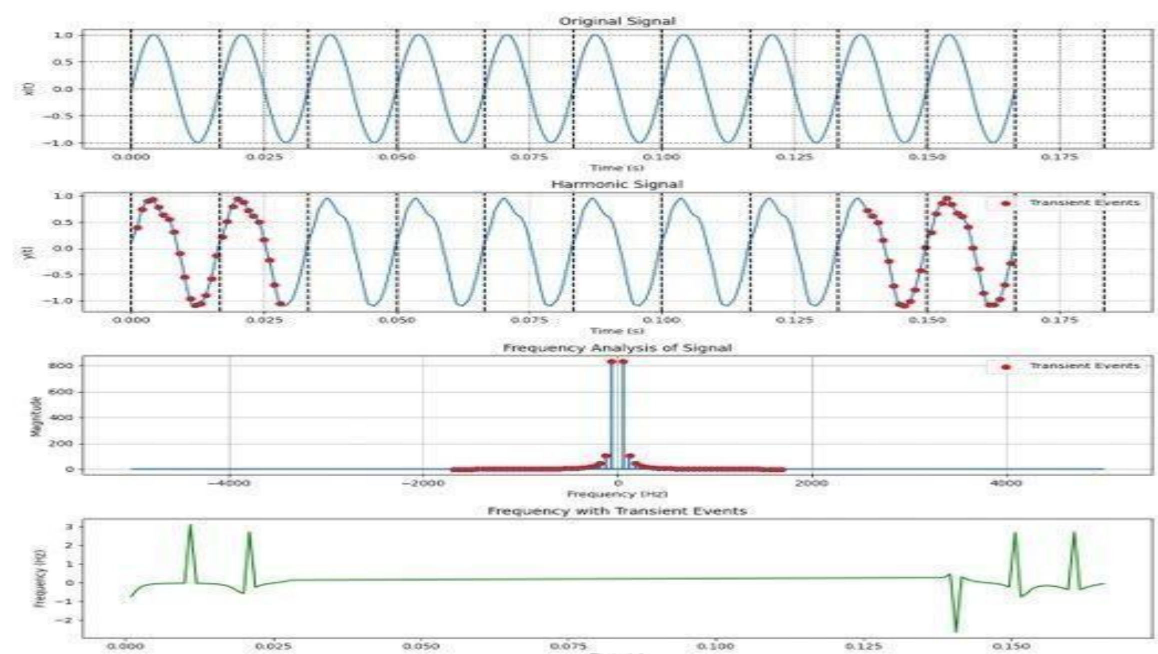

Figure 6: Plots presenting the Original Signal, Harmonic signal, Frequency signal, Transient Frequency signal.

5.2 Phase Modulation (0.1 -2 Hz)

Phase Modulation (PM) in power systems is a technique that translates the data by varying the phase of the carrier signal in response to the modulating signal. The phase of the signal changes with the time due to the phase modulation introduced to the signal phase. This disrupts the amplitude but the signal continues to have sinusoidal wave shape [17]. The first signal represents the original signal with 60 Hz, second is the Phase modulated signal with the transient events detected, third signal is the frequency v/s magnitude which points to the dominant frequency. The fourth plot represents the Transient frequency of the signal during the transient events.

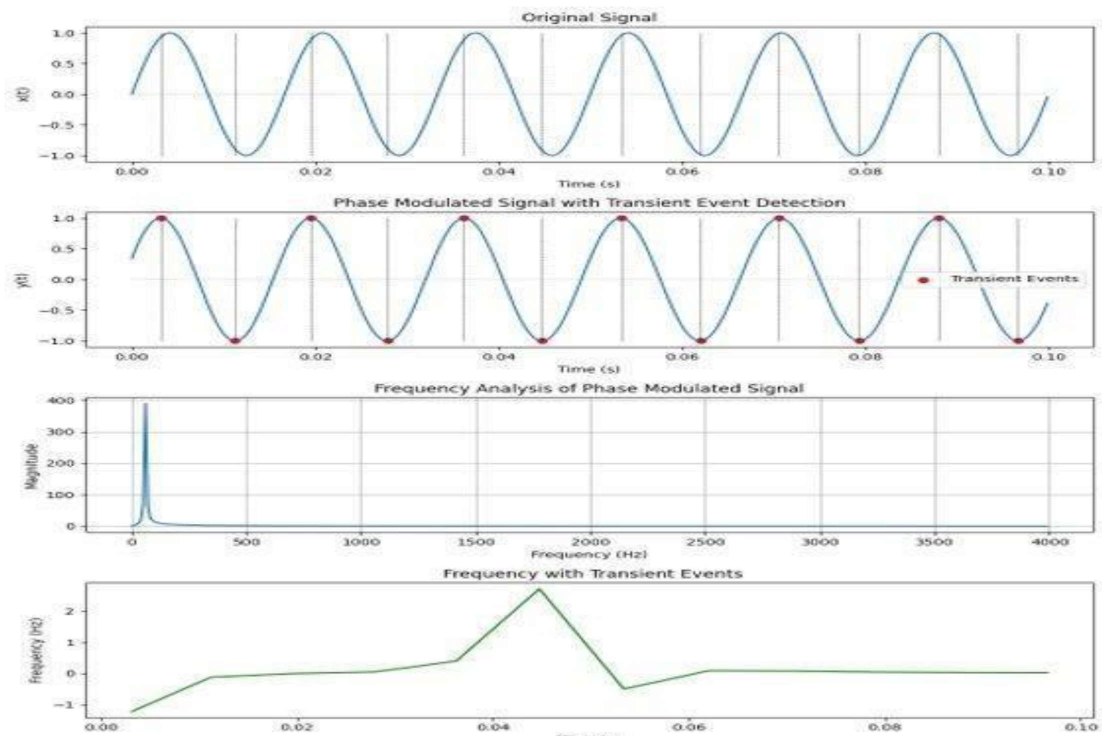

Figure 7: Plots presenting the Original Signal, Phase modulated signal, Frequency signal, Transient Frequency signal

5.2 Amplitude Modulation (0.1 -2 Hz)

Amplitude Modulation (AM) is defined as the wave of the signal transmitted by modulating the amplitude of the signal [17]. AM is one of the oldest widespread technique in Radio and Broadcasting [19]. The modulation in the signal causes the oscillation of waves in the signal, when the frequency of the modulation of the signal is low the amplitude variations are slower (fmin), and the frequency of the modulation is high (fmax)the amplitude variations are higher. The first signal represents the original signal with 60 Hz, second plot represents amplitude modulated signal with the transient events detected, third signal is the frequency v/s magnitude which points to the dominant frequency. The fourth plot represents the Transient frequency of the signal during the transient events.

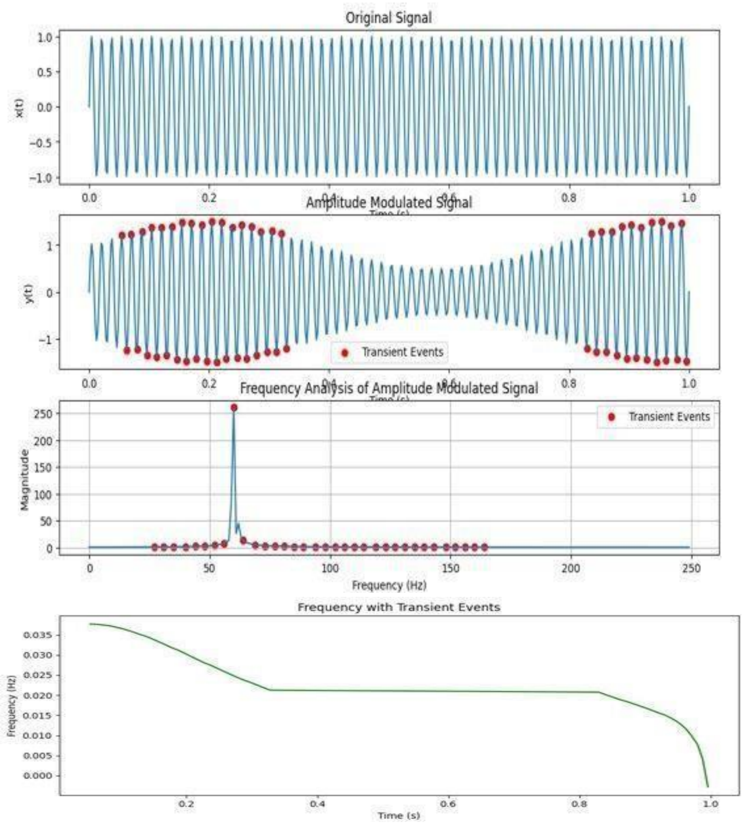

Figure 8: Plots presenting the Original Signal, Amplitude Modulation Signal, Frequency Signal, Transient Frequency signal.

5.2 +/- 10 Deg Phase Step

Phase step Degree is the shift of the angle in the waveform from the original signal with positive or negative degrees. A positive phase step means the waveform is shifted to the left, whereas a negative phase step means the waveform shifted to the right [20]. The first signal represents the original signal with 60 Hz, second plot represents +10 Deg Phase step signal with the transient events detected, third signal is the phase step signal in radians, fourth plot represents which Frequency signal with peaks pointing to the dominant frequency. The fifth plot represents the Transient frequency of the signal during the transient events.

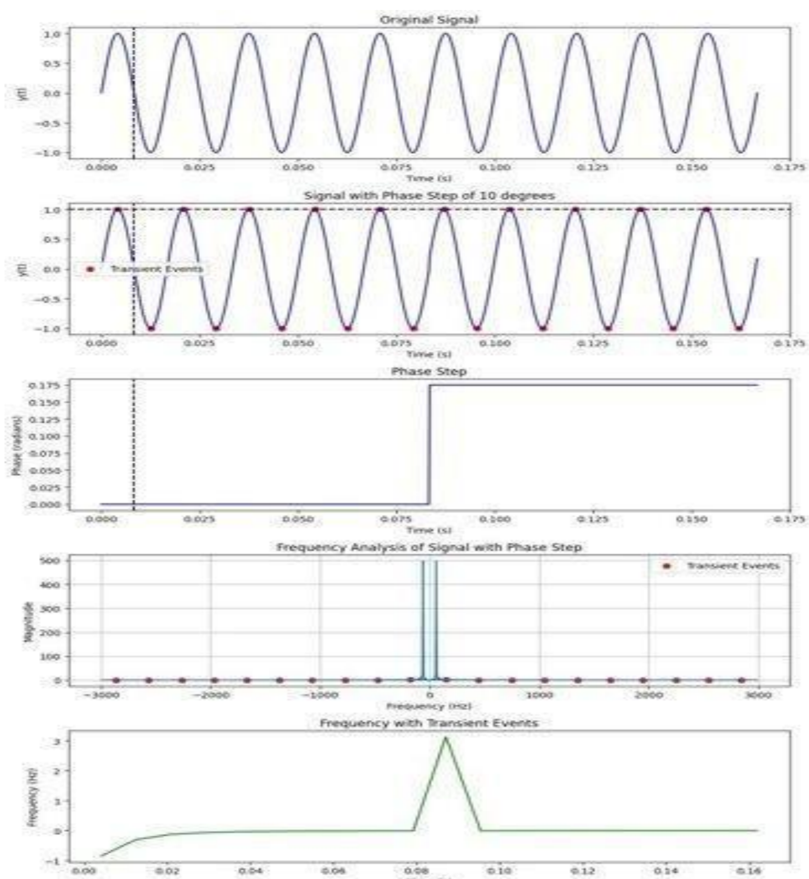

Figure 9: Plots presenting the Original Signal, +10 Deg Phase step signal, Phase Step signal, Frequency analysis signal, Transient Frequency signal.

In the below figure the first signal shows the original signal with 60 Hz, second plot represents -10 Deg Phase step signal with the transient events detected, third signal is the phase step signal in radians, fourth plot represents which Frequency signal with peaks pointing to the dominant frequency. The fifth plot represents the Transient frequency of the signal during the transient events.

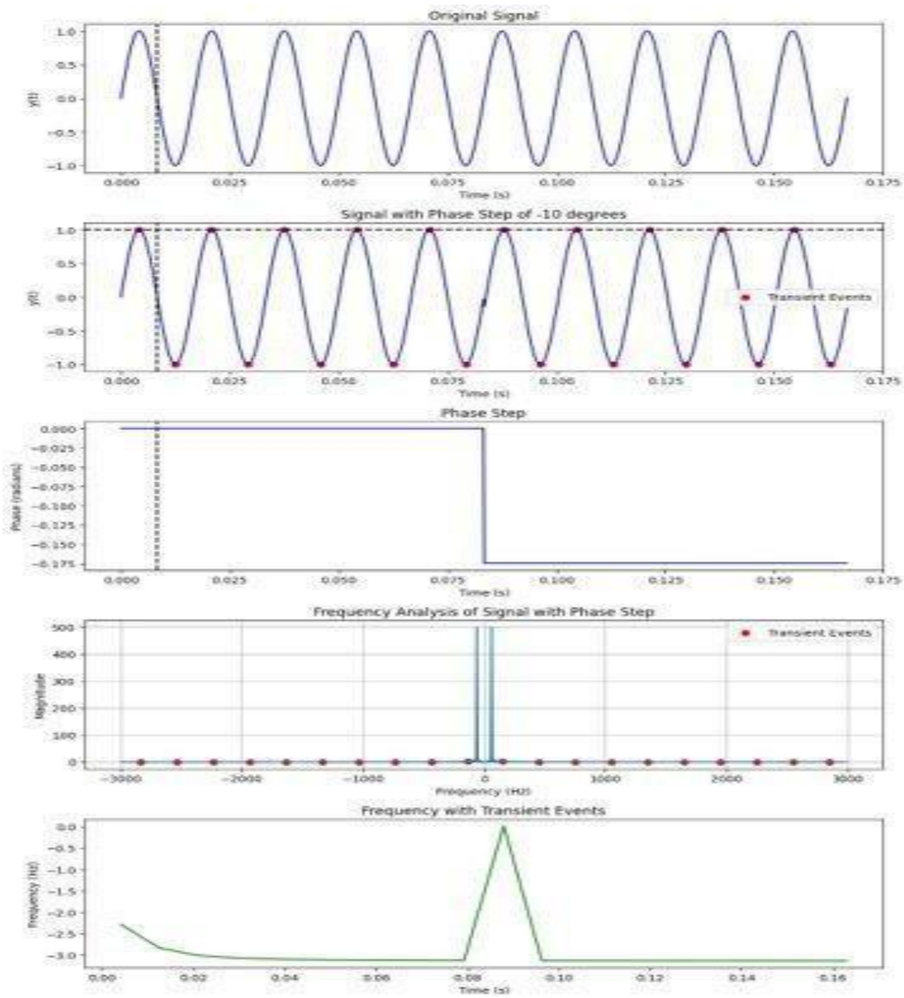

Figure 10: Plots presenting the Original Signal, -10 Deg Phase step signal, Phase Step signal, Frequency Analysis signal, Transient Frequency signal.

Chapter 6: Conclusion

The analysis of the Transient frequency is a very important aspect in power systems engineering in fault analysis, fault detection where the signal gives its valuable information about the sudden changes in the signal which are called transients.

In the study using the powerful machine learning technique known as Random Forest Classifier, and application of signal processing the transient frequency estimation is done by detecting the transient events in the signal. This is the effective methodology to study the behavior, characteristic and detecting the transient event in the signal. An effective methodology for detecting transient event using a robust methodology was developed, using the popular and effective random forest classifier to detect the transient events in the signal, by employing the Data preparation and extraction, classifying the methodology was followed to present the Transient frequency estimation

Random Forest classifier is used to classify the transient events and provides a high level of accuracy, which helps to understand the reliability of the transient frequency signal with the standard test signals.

The ability to detect and analyze the transient frequency benefits and find its application in power systems engineering, for real time monitoring the signals, for fault and anomaly detection. The application of signal processing along with the advanced machine learning technique can help the grid operators to modernize the grids and improve the grid stabilization.

Chapter 7: Future Work

The future works revolves around detecting and monitoring the contingencies and by expanding the data set, real time monitoring to enhance the machine learning adaptability. Furthermore, using the deep learning techniques one can predict the transient event data with more accuracy. Researchers can bring on their innovation techniques in order to recognize the defects, faults, surges in order to provide more grid resilience and reliability which can lead to the continuous improvements.

The study does not come to end but gives an understanding of further exploration, innovation and promising the new possibilities with accurate results that can help the field of power systems and grid operators to create a modernized grid for the stability and reliability.

APPENDIX

1) Harmonic Signal

Table 2: Accuracy and Transient Event times for Harmonic Signals

Accuracy	100%
Transient event times (in seconds)	[0.001 0.002 0.003 0.004 0.005 0.006 0.007 0.008 0.009 0.01 0.011 0.012 0.013 0.014 0.015 0.016 0.017 0.018 0.019 0.02 0.021 0.022 0.023 0.024 0.025 0.026 0.027 0.028 0.1387 0.1397 0.1407 0.1417 0.1427 0.1437 0.1447 0.1457 0.1467 0.1477 0.1487 0.1497 0.1507 0.1517 0.1527 0.1537 0.1547 0.1557 0.1567 0.1577 0.1587 0.1597 0.1607 0.1617 0.1627 0.1637 0.1647 0.1657]

2) Phase Modulation

Table 3: Accuracy and Transient Event times for Phase Modulation

Accuracy	100.00%
Transient event times (in seconds):	[0.003125 0.01125 0.0195 0.027875 0.03625 0.04475 0.053375 0.062 0.070625 0.079375 0.088 0.096625]

3) Amplitude Modulation

Table 4: Accuracy and Transient Event times for Amplitude Modulation

Accuracy	100.00%
Transient Event Times (in seconds):	[0.06212425 0.08817635 0.09619238 0.10420842 0.11222445 0.12024048 0.12825651 0.13827655 0.14629259 0.15430862 0.16232465 0.17034068 0.17835671 0.18837675 0.19639279 0.20440882 0.21242485 0.22044088 0.22845691 0.23847695 0.24649299 0.25450902 0.26252505 0.27054108 0.27855711 0.28657315 0.29659319 0.30460922 0.31262525 0.32064128 0.32865731 0.33667335 0.34669339 0.35470942 0.36272545 0.37074148 0.94589178 0.95390782 0.96192385 0.96993988 0.97995992 0.98797595 0.99599198]

4) +10 Deg Phase Step

Table 5: Accuracy and Transient Event times for +10 Deg Phase Step

Accuracy	100.00%
Transient Event Times (in seconds):	[0.00417084 0.01251251 0.02085419 0.02919586 0.03753754 0.04587921 0.05422089 0.06256256 0.07090424 0.07924591 0.08708709 0.09542876 0.10377044 0.11211211 0.12045379 0.12862863 0.1369703 0.14531198 0.15365365 0.16199533]

5) - 10 Deg Phase Step

Table 6: Accuracy and Transient Event times for -10 Deg Phase Step

Accuracy	100%
Transient Event Times (in seconds):	[0.00417084 0.01251251 0.02085419 0.02919586 0.03753754 0.04587921 0.05422089 0.06256256 0.07090424 0.07924591 0.08792125 0.09626293 0.1046046 0.11294628 0.12128795 0.12962963 0.1379713 0.14631298 0.15465465 0.16299633]

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