A MEASUREMENT-BASED PROCEDURE FOR DYNAMIC DATA IDENTIFICATION OF SYNCHRONOUS GENERATORS

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Degree of Master of Science

Thesis/Dissertation submitted in partial fulfillment of the requirements
for the degree Master of Science in Electrical Engineering

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DECLARATION

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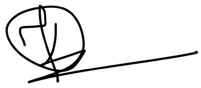

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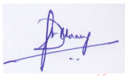

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ACKNOWLEDGMENT

I owe my sincere gratitude to my supervisors, Dr. W.D. Prasad (Department of Electrical Engineering, University of Moratuwa) and Prof. W.D.A.S. Wijayapala (Department of Electrical Engineering, University of Moratuwa) for their encouragement, support, and expert advice to make this research thesis a success.

I would also like to thank all review panel staff of Department of the Electrical Engineering, University of Moratuwa for their guidance and knowledge gave to make this study a success and for the time they have invested in from their busy schedules to evaluate my research work.

This research would not be possible if the guidance and knowledge rendered by Eng. A.I Madawala, Chief Engineer, CEB for this research work. This research would not be completed if the information and test data obtained from the Staff of Kelanitissa Combined Cycle Power Plant (KCCP). Hence, I thank to Eng Janidu Hemachanra for providing me the all requested data for testing conducted at KCCP.

The valuable support given by the superiors and the subordinates at my workplace, Asset Management branch – Generation division of Ceylon Electricity Board is highly appreciated.

I am grateful to my wife and two children for all the sacrifices they have made along the way and also, I would like to thank my parents for all the support given to me during various endeavors in my life.

K.W.K Priyadarshana

February 2022

ABSTRACT

Identification of synchronous generator parameters is a vast area in research topics. In order to model an existing power system network, these parameters are very crucial in identifying the behavior of the system during steady state or dynamic state conditions. When considering the Sri Lankan grid network there exists number of power plant which does not have some design parameters of the synchronous generators and for the older machines the existing value of the parameters might be differ from the design value due to several reasons.

This thesis report is based on the identification of synchronous generator parameters using on line measurement data while giving small step response of around 2%-5% to AVR voltage reference set point. The proposed testing procedure does not create any stress to the machine and can be conducted several times without any special preparation or machine outage.

The proposed methodology to identify the synchronous generator dynamic parameters is developed using the 3rd order SG model defined in the IEEE Standards. Two new system functions have derived to estimate the generator parameter which shows the relationship between the steady state and dynamic state parameters in d-q-0 domain and time domain. The Levenberg Marquart method is used as the Nonlinear least square algorithm to extract the parameters from the measured data. Proposed methodology has applied in MATLAB SIMULINK Simulation environment and in the real environment which test conducted at Kelanitissa Combined Cycle Power Plant, Sri Lanka. The Proposed method results have validated over the results with conventional test results conducted based IEEE Standards on two power plants in Sri Lanka and from the literature of similar tests.

The results of the proposed method have showed good accuracy over the design values and the standard method results. It has showed that the output of the synchronous generator, using the estimated parameters is having a very closer behavior to same with the actual generator parameters. Therefore, this method can use to estimate synchronous generator parameters where the parameters are completely unknown or the machine is too old which may need to identify the existing parameter values.

This study further discusses the reasons for any difference between the design parameter value and the estimated parameter value comparing with the standard IEEE based test results.

This research concludes that the results of the estimated dynamic parameters obtained by the proposed method can be recommended in applying for modelling of the synchronous generators and power systems networks which will give a very close response to the actual response.

Keyword: Parameter estimation, synchronous generators, Levenberg Marquart Method, Online Measurements, Small Disturbance.

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List of Abbreviation

δ	Angle of rotor with respect to terminal voltage /load angle
T_m	Mechanical input torque
T_e	Electrical torque
K_D	Damping factor
ω, ω_0	Rotor speed and nominal speed
e'_q	Internal of stator at transient
E_{FD}	Internal voltage of stator
$X_{d\,,}X_q$	d and q axis reactance
$L_{d\,,}L_q$	d and q axis inductances
L'_d, L'_q	d and q axis transient inductances
$L_{ad\,,}L_{aq}$	Mutual inductance in d and q axis windings
L_l	Leakage inductance
$X_{ad\,,}$	Mutual reactance between the d-axis windings
X'_d, X'_q	d and q axis transient reactance
X''_d, X''_q	d and q axis sub transient reactance
i_d, i_q	d and q axis currents
i_{fd}	Field Current
T'_{d0}, T''_{d0}	Direct-axis transient and sub open-circuit time constant at transient
$\emptyset_f$	Field flux linkage
R_f	Field Resistance
L_{ffd}	Self-inductance of field winding
L_{fd}	Field wingding inductance
L_{afd}	Mutual inductance between stator and rotor windings
L_{f1d}	Mutual inductance between field winding and 1^{st} damper winding
R_f	Field Reactance
X_e, R_E	Line reactance and resistance
v_d, v_q	d and q axis generator terminal voltage
v_{bd}, v_{bq}	d and q axis bus voltage
P	Active power
Q	Reactive Power
I	Generator Current
J	Jacobian matrix
Θ_k	Set of updated parameters at kth iteration
η	Step size
H_{k-1}^{-1}	Inverse of the Hessian matrix.
n	Number of iterations
e	Error vector
N	Number of data points
I	Cost function in NLS algorithm
SG	Synchronous Generator
KCCP	Kelanitissa Combined Cycle Power Plant
AVR	Automatic Voltage Regulator

1.0 INTRODUCTION

A true model of synchronous generators is required for better analysis and study of stability of power system networks. The behavior of the synchronous machines in a power system network is defined by its own parameter values. These parameters reflect the performance of the machine during steady state and transient conditions. Hence identifying the existing values of the synchronous machine has become a crucial requirement in power utilities.

1.1 Modelling and Parameters identification of synchronous generators

In any engineering field, modeling is a true essential part. Modelling of synchronous generator has become vast area in research and development studies. Steady state and dynamic state analysis of synchronous generators is very important in identifying the power system networks and the synchronous generator alone. The parameters of the conventional synchronous generator model can be determined according to recognized theories, such as the Park transformation that is mainly tested when the Machine is not in use. The traditional approach in electrical engineering is to use the Park model where modeling of the synchronous generator is required. Park transformation is typically used in following areas.

- Operation during the steady state specially in voltage regulation and exciter response analysis
- Analysis of power failures and faulty operations
- Determine the faulty cases of the electrical machine windings
- Response of the synchronous generator and power system during small disturbance and large disturbance
- Designing and research works in synchronous generators, exciters and PSS related controllers.

Except for the park model there are number of different models available and selection of the model is completely depended upon the aim of the results intended by the user. However, the expectation of modelling a synchronous generator may have several intentions. Mostly through the valid modelling of these machines, it will open vast area on research developments on stability of power system networks. In power system networks, several changes may be introduced by time to time. There can be new power plants, new transmission lines or new load centers introduced in the system network. This can be led to change the behavior of the individual machines and system as a whole during steady and dynamic conditions. So, if the utilities have a valid model of the synchronous generators and power system network then it'll be able to study and forecast the behavior of the system network before such new components introduced to the system. Additionally in case of unintended operation or fault occurred in the system, those can be study thoroughly and can take further improvements in theoretical and methodical aspects.

The valid model of the synchronous generator is represented by number of parameters which will define the behavior in steady state, transient state and sub transient state. In total there are around

63 parameters which will define the behavior of the synchronous machine. In order to obtain all those parameters, a complex and higher order model is required. In most cases at least the following parameters are considered in modelling of synchronous generators.

- X_d and X_q - d and q axis synchronous reactance
- X_d' and X_q' - d and q axis transient synchronous reactance
- X_d'' and X_q'' - d and q axis sub transient synchronous reactance
- T_{d0}' and T_{q0}' - d and q axis open circuit transient
- $T_{d0}''$and T_{q0}'' - d and q axis sub-transient time constants
- T_d' and T_q' - d and q axis short-circuit transient time constants
- $T_d''$and T_q'' - d and q axis short-circuit sub transient time constants

Above parameters reflect the characteristic of the synchronous generator at different operation conditions. Designer and Manufactures are very concern on theses parameters on the design stage of these due to several reasons. In addition to the behavior of the system, these parameters will design the conductor sizing, characteristic of the conductor and material of the conductors which will reflect in the cost of the synchronous generator.

1.2 Motivation

In the Park model, it needs to have at least three resistors and three inductors in the model. If the machine damping effect is also included in the model, at least two more additional resistors and two additional coils must be introduced. Therefore, the synchronous generator used in the design phase requires complex calculations and a large amount of data. Most of these design materials are not available in the Generator manual in the power plants.

Standard tests have been developed to determine the parameters of synchronous generator. In order to perform these tests, machine need to take outage from the system. Hence their will no power generation from that machine for that particular outage period. Therefore, it needs to have a special outage planning considering the availability of other machines in the grid. During this standard test machine has to undergo several load rejections tests and sudden short circuit tests. When the system operators are struggling to meet the demand from the available power plants, it may lead to wait for longer time period to take outage of some generation units specially when the machine is old and is running under controlled conditions. Taking machine outage from the system is not beneficial for the system as well. If the plant is base generation power plant, then taking an outage is challenging task. Conducting load rejection and short circuits tests will also create stress to the machine, therefore the power plant owners are reluctant to conduct such tests.

Therefore, finding an online method which will not stress the machine to determine the generator parameters is a strong requirement in the field. Online methods for identifying machine parameters are very attractive to utility companies because they have the least interference with normal generator operation. If the test is possible to conduct while the machine is running at normal generating operating conditions, then the generator parameters can be calculated without making any impact to the system generation requirements. Additionally, this type tests can be repeated until it gives satisfactory results.

This report contains a procedure which can conduct the test while the machine is running in normal condition and giving a small step response of around 2-5% to AVR reference voltage set point. Obtained field measurements are applied into two derived system functions and basic field voltage equations under the dynamic conditions. Output of these functions are used as the input to the mathematical estimation algorithm which is known as Levenberg Marquardt method.

1.3 Project Objective

Objective of this research is to develop a methodology to estimate steady state and dynamic state parameters of the synchronous generator parameters by creating a small disturbance while the machine is in running condition. Without any special preparation or modification, it shall be able to derive the synchronous generator steady and dynamic data by creating a small step response to the AVR refence point.

Accuracy of the proposed method results is validated using the IEEE Standard test procedure results and the Manufacture given design data.

1.4 Thesis Outline

Chapter 2 illustrates the comprehensive literature review related to synchronous generator parameter estimation methodology. In here the IEEE standards based conventional testing method and online measurement methods are discussed.

Chapter 3 presents the proposed methodology and derivation of the equations used in the method. Applying the measurements to the NLS algorithm is also discussed in this chapter.

Chapter 4 describes the application of the proposed method in MATLAB SIMULINK Simulation environment and in real environment where the test conducted at Kelanitissa Combined Cycle Power Plant, Steam Turbine Generator unit. Further it analyses and validate the results in comprehensive manner with the Standard IEEE test results and similar literature results.

Chapter 5 presents the conclusions of the study.

2.0 LITERATURE REVIEW

There are many researches related to identification of synchronous generator parameters. It can be mainly divided into two categories which are estimation methods used while the machine is in standstill and running condition.

2.1 History of Development of Synchronous Generator Models

The Park model is not the only model used to model a synchronous machine. There are several other models developed by William B. Jackson and Robert L. Winchester for the q-axis and d-axis equivalent circuits of synchronous generator circuits. Yao-nan Yu and H. A. M. Moussa are also two researches who have made important contribution in developing equivalent circuit of synchronous generator which can use to derive the generator parameters.

Methodology to obtain the synchronous generator parameters by creating a sudden short circuit at generator terminals and using the output signals of that test is conducted in 1977 by two electrical engineering professors, O.T.T.Tan and C.C.Lee. In 1981, Parameter identification of synchronous generator using frequency measurements while the machine is running conditions is introduced by Paul L. Dandeno which was conducted in two large turbine stations. T. Nishiwaki who has done many researches on Kalman filters during the same period has used a vast range of Kalman filters to evaluate dynamic parameters creating step responses while machine is running at steady state condition. Another option is to use the finite element method, where the magnetic circuit in the synchronous machine is modeled at the micro level and converted at the meso level.

2.2 Synchronous Generator Models

Synchronous generators usually consist of three-phase armature windings in the stator and winding in the rotor which also referred as field winding. In addition, the synchronous generator includes other conductive paths which currents can be generated during a short circuit. This current can be flow through the pole-face damping coils or damper bars. These currents can be generated in solid form in the rotating parts of the generator. Considering this damping phenomenon into modelling, it'll give more accurate representation of the generator. However, it has higher complexity and large amount of calculation. If the transients and sub transient conditions are not required then these models can be simplified as per the intended level of accuracy required in the synchronous generator model. In any basic type of analysis, the armature current and voltage are converted into two sets 90 degree apart variable, a group consistent with the magnetic field of the field winding, called d axis and another set of electrical positions rotated 90 degrees apart from the field winding which is called the q axis.

The simplest representation of synchronous generator is that it assumed there is only d axis current component in armature and rotor winding and no other current paths like damper winding current are available.

There are several types of synchronous generator models are available. As per the IEEE Guide for Synchronous Generator Modeling Practices and Applications in Power System Stability Analyses Standard document [2] it has declared synchronous generator models as follows,

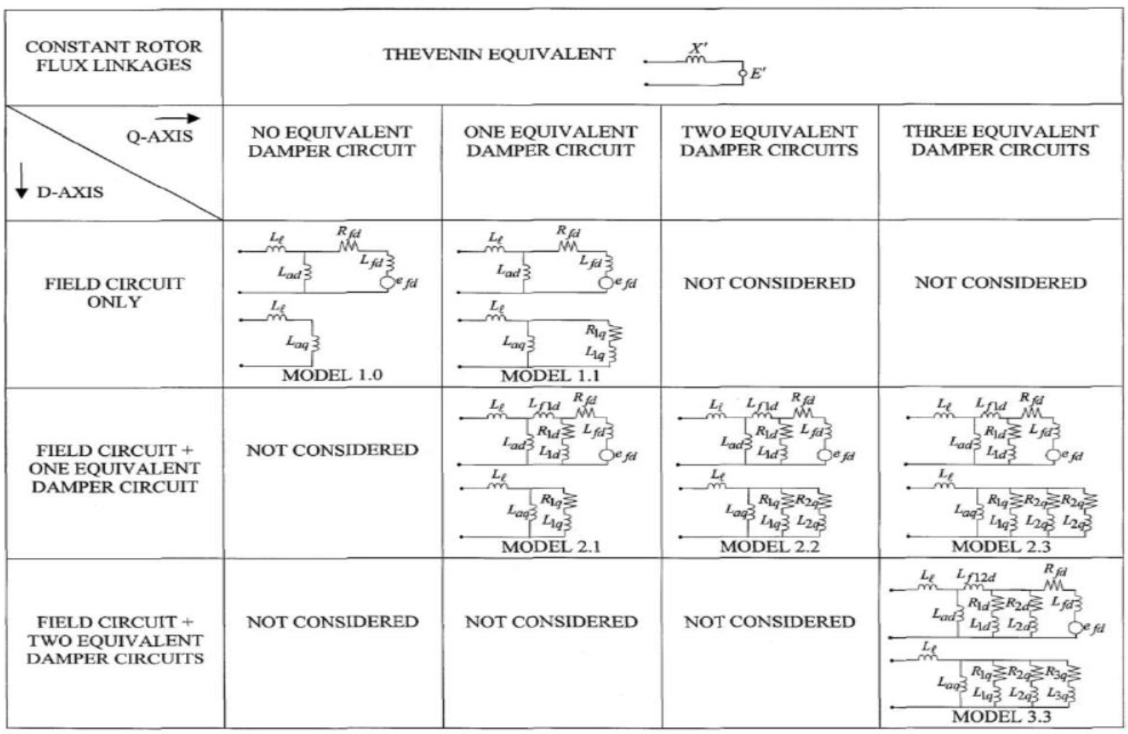

Figure 1: Selection of Generator Models as per IEEE Standard

Following figures show the difference of each model commonly used in synchronous generator modelling.

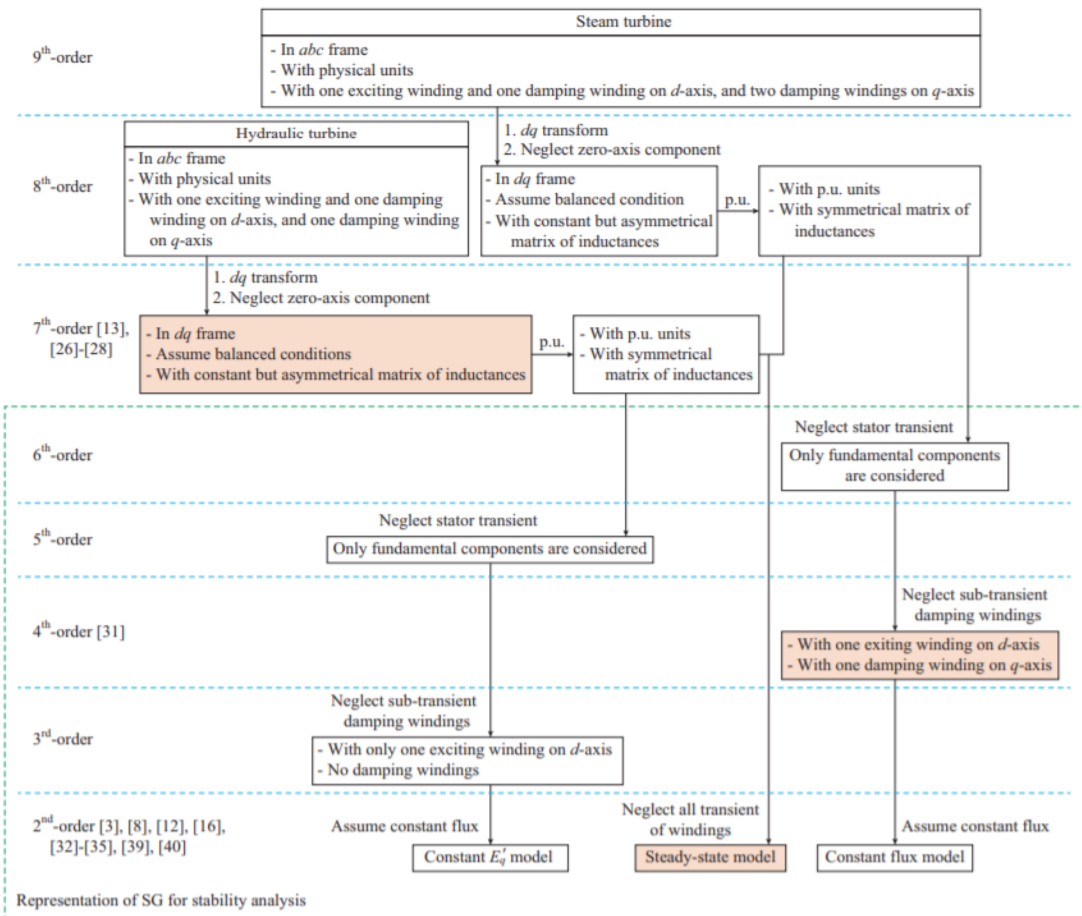

Figure 2 : Summary of eight different order levels for synchronous Generators

2.3 Selection of the appropriate model for this research study

Selection of the Generator model is complete depend on the aim of the final results. If it required to obtain all the parameters of the synchronous generator then selection of Model 3.3 as per the IEEE standard is acceptable. Therefore, there is no defined nonlinear structure to obtain the behavior of the synchronous generator when dealing with practical concerns. Higher degree of the model would be beneficial if the sub transient conditions are interested. The number of the order or the complexity depend on how much non nonlinearities can be developed for the synchronous generator.

During this study only transient condition will be considered. Therefore, sub transient parameters will be not estimated during this study. As only the transients are considered, damper winding parameters can be neglected. Hence the most suitable model for this research study is 3rd order SG model. Neglecting the damper winding parameters, the 3rd order model can be expressed in following three equations [9].

$$\frac{d\delta}{dx} = \omega_0 \Delta\omega$$

$$\frac{d\omega}{dx} = \frac{1}{2H}(T_m - T_e - K_D \Delta\omega)$$

$$\frac{de_q'}{dx} = \frac{1}{T_{d0}'}(E_{FD} - e_q' \quad - (X_d - X_d')i_d)$$

In higher order model, the synchronous machine is described by higher number of equations which will lead to have higher accuracy. Model which describes the generator with 8th order model is determining all the parameters of SG. For that it involves extensive calculations. In 8th order model 61 parameters are estimated. Each of the parameters shows very complex relationship in terms of nonlinear relation with the physical parameters. In practical noisy environment, extracting the true signal while having the effect of the parameters is more difficult and challenging task. Even though it is good research area for further developments.

2.4 Mathematical Estimation Techniques

In engineering applications, estimation methods such as linear least square method, nonlinear least square method and maximum likelihood method are commonly used. When mathematical model is used in estimation algorithms, then that model shall be able to represent the actual state of the system function using the given inputs. Due to this reason, the state estimation algorithm is conducted in iterative way by using the updated value for the state variable upon the given inputs to the system which is taken from measurements.

2.4.1 Selection of Suitable Non-Linear Estimation Method.

Several Mathematical estimation algorithms have developed in over the years in various forms. One method is direct search algorithm which use the calculation of the loss function values only. The loss function in nonlinear regression is the function that minimized by the algorithm. It can be minimizing the sum of squares or user defined loss function to minimize another function. Usefulness of these direct method is that it is easy to understand and implement. However, this cannot be used where the gradient function is required. This does not use derivatives of the variables. Therefore, this method usually has slow convergence than other methods.

When it comes to Newton's Method, it uses the second derivative of the loss function or estimate the finite difference technique.

The Newton's method is derived as,

$\Theta_k = \Theta_{k-1} - \eta_{k-1} H_{k-1}^{-1} \Theta_{k-1}$

Where,

Θ_k set of updated parameters at k^{th} iteration

η_{k-1} step size

H_{k-1}^{-1} inverse of the Hessian matrix. Hessian matrix defined as the multiplication of the Jacobian matrix transpose and the Jacobian matrix (J^T *J)

In Newton's method this η which known as the step size is set to one (1) in classic applications

Newton's method is directly use second order Taylor series expansion of the loss function. In nonlinear applications when the η equals to 1, it can be too small or can be too large depending on the variable behavior of the loss function

Therefore, to improve the convergence and the robustness of the method, η is calculated using line search method. However, the issue with the Newton method is it will decrease the robustness of the loss function in negative definite. Loss function decrease only for the positive definite of the Hessian matrix. To avoid this issue, modified Newton's method is developed such that the hessian matrix is replaced with vectorize Hessian matrix which can apply for the both positive and negative elements. This is faster method which use for nonlinear optimization.

In the nonlinear least square problem this hessian matrix further developed as,

$\underline{H} = 2 * \underline{J}^T \underline{J} + 2\underline{S}$

Where $\underline{S}$ is defined as the residual error. Using this residual error for the estimation, it is recognized as more accurate and faster convergence method.

When it comes to the Gauss Newton method, it is defined as,

$\Theta_k = \Theta_{k-1} - \mu_{k-1} (J_{k-1}^T J_{k-1}) J_{k-1}^T e_{k-1}$

Θ_k set of updated parameters at k^{th} iteration

μ step size

J Jacobian matrix

e error vector of output signals

This encounters the residual error of the said two set of measurements and do extra calculation in computation of the error. This extra calculation shall be taken part in algorithm if this residual error is large enough to make impact to the final results. In most nonlinear least square applications this gauss newton method and the Levenberg Marquart method is recommended to use to obtain more accurate results.

2.4.2 Levenberg Marquart Method

The Levenberg Marquart method is an extension of the gauss newton method, which defines as,

$$\Theta_k = \Theta_{k-1} - \mu_{k-1}(J_{k-1}^T J_{k-1} + \alpha_{k-1} I) J_{k-1}^T e_{k-1}$$

α positive constant of NLS

I $e^T * e$

All other variables are the same as mentioned in above paragraphs.

Jacobian Matrix defined as,

$$J^T = \begin{bmatrix} \frac{\partial y_1(1)}{\partial \theta_1} & \cdots \frac{\partial y_1(N)}{\partial \theta_1} & \frac{\partial y_2(1)}{\partial \theta_1} \cdots & \frac{\partial y_2(N)}{\partial \theta_1} \\ \vdots & \vdots & & \vdots \\ \frac{\partial y_1(1)}{\partial \theta_n} & \cdots \frac{\partial y_1(N)}{\partial \theta_n} & \frac{\partial y_2(1)}{\partial \theta_n} \cdots & \frac{\partial y_2(N)}{\partial \theta_n} \end{bmatrix}$$

The addition of the $\alpha_{k-1} I$ is a regulation technique added to the algorithm to improve the accuracy of the final results. For smaller values of the α_{k-1},this algorithm becomes Gauss Newton algorithm and for large α_{k-1}, it becomes gradient based Levenberg Marquart method. For larger value of the $\alpha_{k-1,}$ the $J_{k-1}^T J_{k-1} + \alpha_{k-1} I$ matrix tends to become positive definite and it'll lead to linear direction to the optimum result. Therefore, correct determination of the α_{k-1} is important. As a start, random positive value is selected for the α_{k-1}. Then for each iteration α_{k-1} is reduced by some factor if the parameters are approaching to the optimum value. If the reduction of α_{k-1} is gives faulty results, then α_{k-1} is increased by some factor until the result directs to some optimum result. Due to the fast convergence and the robustness this Levenberg Marquart method, this is applied in lot of application which relates to nonlinear optimization problems.

This Nonlinear least square method is used in this research study.

2.5 Useful guide books on the research topic

P. Kundur's Power System Stability and Control book have illustrated a comprehensive study on synchronous generators in terms constructions, steady and dynamic behavior, the role played by the generator parameter at different loading conditions and modeling aspect of SG. It also describes the synchronous generator modelling including exciters and governors, unit representation, equivalent circuits and steady and transient analysis of synchronous generator etc...

Anderson, Agrawal, and Van Ness's Sub Synchronous Resonance in Power Systems book provides an extensive coverage of synchronous generators and machines. It has dedicated chapters to describe the synchronous machines and provide comprehensive analysis of d-q axis equations, synchronous generator modelling. It also covers Park's transformation in detail. It also consists of separate chapter on generator parameter calculations, from measured field test data and sample test results.

2.6 Overview of the Literature available on online measurement methods

Prof A. Keyhani is one of leading professor who have conducted many researches on identification of synchronous generator parameters. Most of his studies on synchronous generator parameter estimations are based on online measurements. Keyhani uses a variety of different methods to study the estimation of parameters and has published a large number of publications on this topic. He has used standstill frequency response data to estimate generator parameters. Using the straight and square transportation technique, the relationship between generator parameters and the time domain coefficients of the transfer function has been developed. Solving those functions of equations, the final estimated results were obtained.

Data corrupted by noise can cause difficulty in estimating parameters. Hence it has to be evaluated carefully without disturbing the impact of the particular parameters. Another approach used by Keyhani is to use maximum likelihood method to derive parameters from the field data taken from highly noisy environment. The results reveal that even if the data is corrupted by noise, a relatively accurate set of variables can be obtained.

Keyhani has discussed a case study in [4] using SSFR data from 722 MVA generator to evaluate the performance of the Maximum likelihood method. In this approach also maximum likelihood method has been proven that the better estimation can be obtained even the field measured data is having high SNR ratio. Using a 5kVA salient pole synchronous motor, the same type of tests has been conducted. Maximum likelihood algorithm and stand still frequency response data is used to identify the SG parameters.

Several tests have introduced to identify the generator parameters at standstill conditions. Keyhani has introduced a test method such that the step signal is given to the field voltage input to determine the linear parameters of SG. [6]. Input to this model is the field voltage and it's given as a step input signal. Output signals are the generator terminal volage and field current. The time constants and other parameters of the equivalent circuit have derived from this research.

Another application of small step disturbance response and maximum likelihood estimation method is conducted to identify synchronous generator parameter in online is mentioned in [5]. In this research a linear model has developed rather than a nonlinear model. As the next step, coefficients of that linear model are determined. Later, the saturation effect is considered in the model by considering the mutual inductances under different loading conditions. As per the results, it has proved that when the saturation effect is considered into the modelling, the output of the simulated model shows very accurate behavior to the actual behavior.

Using artificial neural network system is also popular approach used by many researches. Keyhani, Demcko and Tsai has developed a neural network considering a saturated generator model. [7]. First this neural network has to be well trained. Once it is well trained it can re arrange into intended pattern. The model used in this network is a downstream network and the learning system is in the form of incorrect distribution. In addition, the training samples were taken by creating a small step response while the machine is in running condition and the using maximum likelihood algorithm. According to this research, expect for the accurate results obtained, it shows that when saturation model is considered in modelling, it can forecast the nonlinear behavior in the machine which are not trained during the neural network training.

Most of the experiment studies based on this topic is conducted on laboratory level machines. Very few were identified which was done in large capacity machine. In [8], it has focused on field measurement obtained from the test data conducted on high-capacity synchronous generators. The research has introduced a method for estimating machine parameters using previously available data and real-time operating data. In here, the model of the study is single machine infinite bus system. The research shows that data corrupted by noise can be processed to a certain extent. Even there are method of extracting parameters from a noisy environment, there is a particular SNR level which the effect of the parameters cannot extract from the measured signal. The maximum recursive likelihood technique is used to calculate the armature circuit parameters. From these estimates, the output error estimation technique is used to evaluate the field winding and damper winding parameters. The results show that even if the data is very corrupt, the estimated variables and actual variables are very consistent. However, in this study the validation of the results has been conducted by using similarity of the estimated parameters curves and real measurement curves or simulated measurement with actual parameter values.

2.7 Conventional method for parameter estimation based on IEEE Standards

IEEE standards has given a guide to estimate synchronous generator dynamic parameters which is widely used in the field. However due to the reason discussed in section 1.5, this test procedure is much reluctant to use by the plant operators. When the machine is old for 20 or 30 years old, there is a risk of conducting such tests. Anyhow this method is a proven accurate method to estimate the generator parameters. Additionally, it is possible to estimate higher number of parameters which is beneficial to model a synchronous generator. Hence this method is currently used in order to get more accurate existing parameter values of the synchronous generator.

The test is performed by conducting load rejection tests, also known as the dump tests and sudden short circuit tests which is based on the IEEE Standards. Steady state, transient state and sub transient state reactance ($X_d, X_q, X'_d, X'_q, X''_d$ and X''_q) , transient and sub transient state time constants in open circuit condition (T'_{d0}, T'_{q0}, $T''_{d0}$and T''_{q0}) and short circuit condition (T'_d, T'_q, $T''_d$and T''_q) are estimated in this study.

The main focus of the load rejection test is to determine d and q axis steady state, transient and sub transient reactance. Additionally, the same test results can used to determine open circuit transient and sub transient time constants. Mainly this load rejection test consists of,

1. Direct axis dump test
2. Quadrature axis dump test
3. Arbitrary axis dump test

The parameters are obtained using the generator terminal voltage curve. During these tests, excitation system is kept in manual mode and field current must be remain constant. During this test, generator breaker will open and at the same time the turbine will also trip. Load angle has to be measured during the test.

1. Direct (d) axis load rejection test

   - The generator parameters of X_d, X'_d, X''_d, T'_{d0}, and T''_{d0} are estimated from this test.
   - During this test, the generator shall operate at maximum reactive power in leading side or the lagging side with no active power generation. Purpose of this operation mode is to make align the stator current in the direct axis. So that current component will have only d axis parameters. Using the measurement plot of the voltage curve and field current curve, it is possible to calculate X_d, X'_d, X''_d, T'_{d0}, and T''_{d0}

Generator Parameters are calculated using the envelop of the generator voltage as follows,

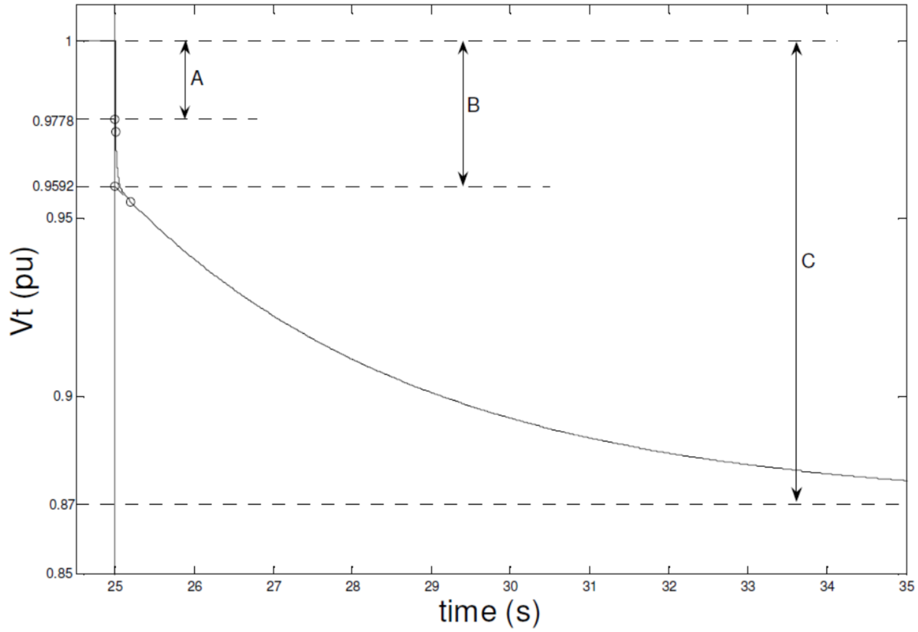

Figure 3 : Terminal voltage at load rejection

$$X_d = \frac{C}{it_0} \qquad X'_d = \frac{B}{it_0} \qquad X''_d = \frac{C}{it_0}$$

Here it_0 is the armature current recorded just before the load rejection.

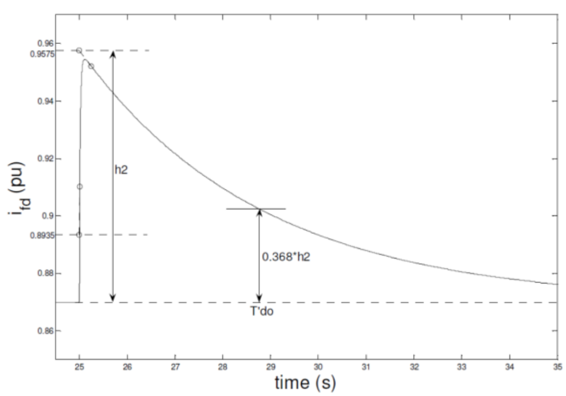

Figure 4: Field Current at load rejection

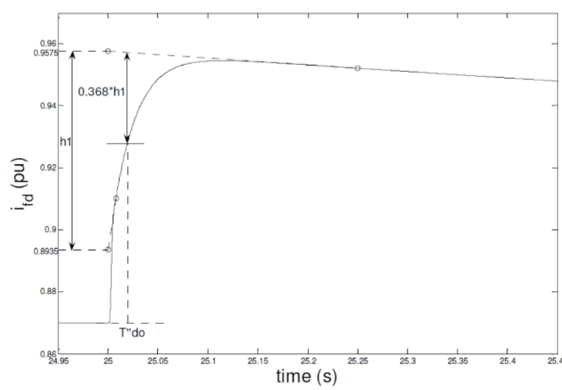

Figure 5 Amplification of Fig 4

The time constant T'_{d0} and T''_{d0} taken as the time required to decrease the voltage 0.368 times from its initial value. In the above graphs initial values can be obtained as h_1 and h_2.

.

2. Quadrature (q) axis dump test

- The parameters X_q and X_q'', are estimated from this test.
- During this q axis dump test, armature current will have only the q axis components by adjusting the field current and the reactive power so that the power factor angle and the load angle is same. Using the measurement plot of the Generator voltage and Reactive power, it is possible to calculate X_q and X_q'',

Generator Parameters are calculated as follows,

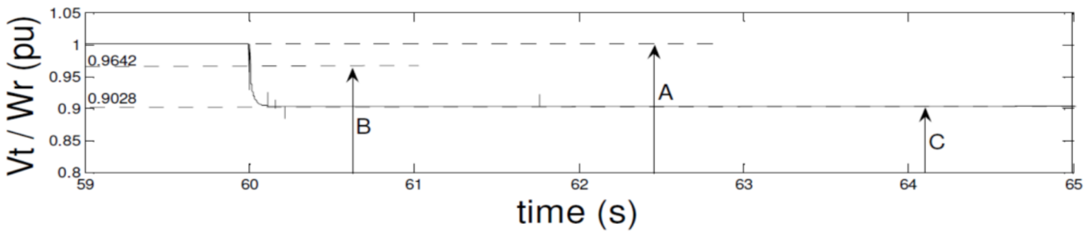

Figure 6: Voltage/Speed curve at load rejection

$$X_q = \frac{\sqrt{A^2 - C^2}}{i_{q0}}$$

$$X_q'' = \frac{\sqrt{A^2 - C^2} - \sqrt{A^2 - B^2}}{i_{q0}}$$

Here i_{q0} is the q axis stator current recorded just before the breaker open.

3. Arbitrary axis load rejection test

During this test X_q, X''_q and T''_{d0} will be estimated. During this load rejection test, machine is disconnected while the stator current has any value so that it'll have both d axis and q axis components.

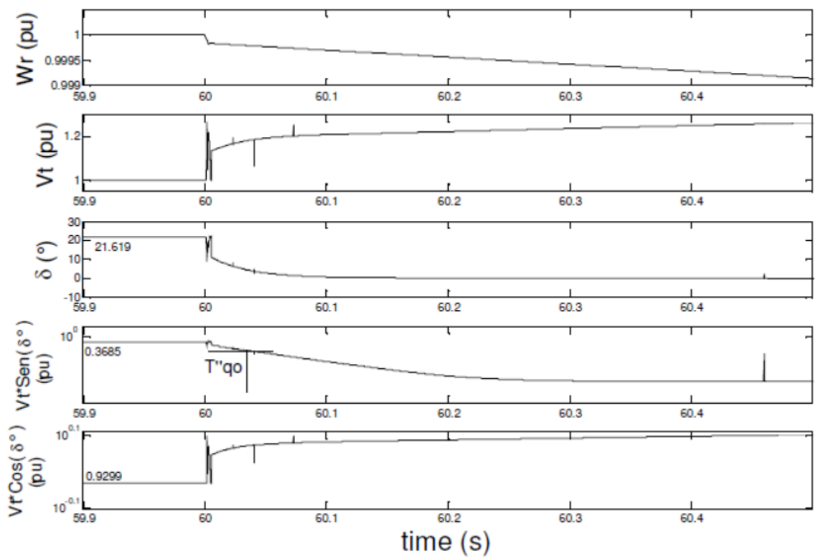

Figure 7: Load rejection at arbitrary operating point

Parameters are calculated as follows,

$$X_q = \frac{V_t sin\delta}{i_{q0}}$$

$$X''_q = X_q - \frac{(V_t sin\delta)'}{i_{q0}}$$

The T''_{d0} is the time required which the voltage to decrease 0.368 time from its initial value.

Chapter Summary

This chapter discuss the development of the synchronous generator models by time to time, the standard models defined in IEEE Standard, the factors which need to consider in selecting the appropriate model and the model which has selected during this study. Further this discusses the mathematical estimation techniques used to extract parameters from a nonlinear structure. Overview of the literature available on this area of study has elaborated as summary with their approach and techniques. Conventional method to identify the generator parameters which based IEEE standards has also discussed in detail. Next chapter describe the proposed methodology to estimate synchronous generator parameters.

3.0 PROPOSED METHODOLOGY TO ESTIMATE PARAMETERS OF SG

As discussed in section 1.3, synchronous generator model used in this study is 3rd order synchronous generator model.

Following Assumptions have made during this study.

1. This study will focus on estimating X_d, X_q ,X_{ad} , X_f, R_f ,X'_d and T'_{d0}. All these parameters are related to transient conditions. Hence the fast responses are not required for this study. Therefore, effect of the damper windings which plays vital role during sub transient conditions can be neglected.
2. Only the rate of change of field flux is considered for the field voltage buildup equation. Induced flux due to stator current dynamics in the field winding is neglected. This is acceptable since the disturbance is created at the AVR reference point and change of the field voltage is initiated from the field flux. Therefore, the contribution to the field voltage buildup is higher from the field flux comparatively to the induced flux due to the stator currents.
3. Stator resistance and Line resistance is neglected since the value is comparatively small and it'll helpful to simplify the model equations.

Hence considering the above assumptions, 3rd order model can express as following three equations [9],

$$\frac{d\delta}{dx} = \omega_0 \Delta\omega$$

$$\frac{d\omega}{dx} = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega)$$

$$\frac{de'_q}{dx} = \frac{1}{T'_{d0}}(E_{FD} - e'_q \quad - (X_d - X'_d)i_d)$$

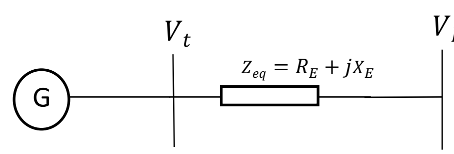

Figure 8 : Simplified Structure of Study

Where,

$$e'_q = \frac{X_{ad}}{X_f}\omega\emptyset_f$$

$$T'_{d0} = \frac{X_f}{R_f\ \omega}$$

$$X'_d = X_d - \frac{X_{ad}^2}{X_f}$$

$$E_{FD} = X_{ad}\frac{V_f}{R_f}$$

Derivation of above three equations is shown in later part of this chapter.

3.1 Derivation of the Mathematical function to estimate X_d, X_q *and* X_{ad}

Electrical torque can be defined as,

Apparent Power, S $= \widetilde{E_t} * \widetilde{I_t}$

$= (v_d + jv_q)(i_d - ji_q)$

$= (v_d i_d + v_q i_q) + j(v_q i_d - v_d i_q)$

Hence Active power and reactive power can write as,

$P_t = v_d i_d + v_q i_q$ ………………………………. (1)

$Q_t = v_q i_d - v_d i_q$ ……………………………….. (2)

Electric Torque T_e $= P_t/\omega$

Substitute equation (1) above, at steady state conditions,

$$= \frac{v_d i_d + v_q i_q}{\omega} \cong \frac{v_d i_d + v_q i_q}{\omega_0}$$

P $= T_e\omega_0 = v_d i_d + v_q i_q$ ………………………. (3)

Generator terminal Current $I_t = \frac{\sqrt{P^2+Q^2}}{V_t}$

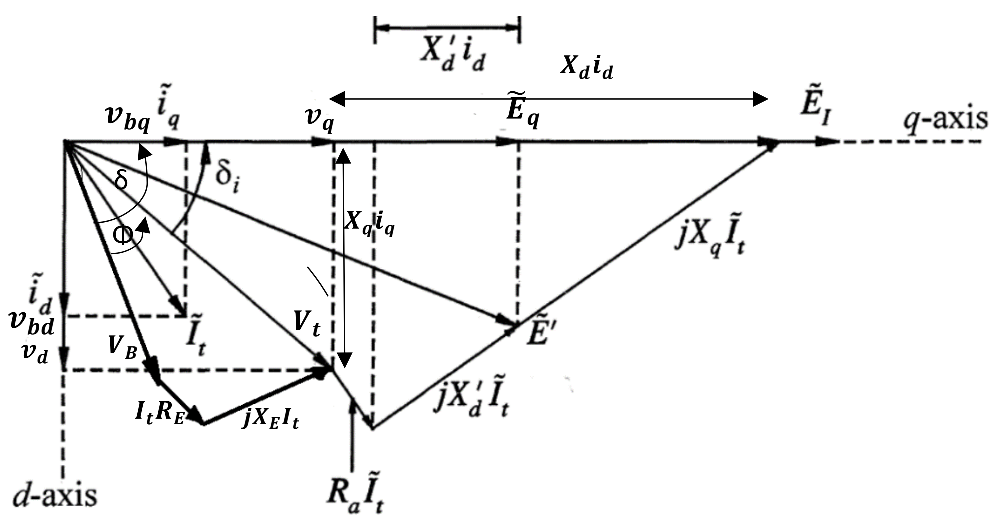

Figure 9 : Phasor diagram for structure of fig 8

Using the Phasor diagram in figure 9, it can show that

$v_d = V_t \sin\delta$ ……………………………………(4)

$v_q = V_t \cos\delta$ ……………………………………(5)

From fundamental equations,

$V_t = v_d + jv_q$

$V_B = v_{bd} + jv_{bq}$

Considering the structure of study as per figure 8,

$V_t = V_B + (R_e + jX_e)I_t$

$v_d + jv_q = (v_{bd} + jv_{bq)} + (R_e + jX_e)(i_d + ji_q)$

Resolving into d and q components gives,

$v_d = R_e i_d - X_e i_q + v_{bd}$

$v_q = R_e i_q + X_e i_d + v_{bq}$

Using Phasor diagram in figure 9, it can show that

$v_{bd} = V_B sin\delta \; and$

$v_{bq} = V_B cos\delta$

Hence, neglecting the line resistance, it gives,

$v_d = V_B sin\delta - X_e i_q$

and using phasor diagram in figure 9 and neglecting the line resistance, it can show that,

$v_d = X_q i_q - X_e i_q = \left(X_q - X_e\right) i_q$ .... (6)

$v_q = X_e i_d + v_{bq} = (X_q - X_e) i_q$

The stator voltage for v_q can be written as

$v_q = \frac{d\Phi_q}{dt} + \phi_d w_r - R_a i_q$ [9] .... (7)

Under the balanced steady condition equation above (7) becomes,

$v_q = \phi_d w_r - R_a i_q$... (8)

Also, Stator flux linkage equations can be written as,

$\phi_d = -(L_{ad} + L_l) i_d + L_{ad} i_{fd} + L_{ad} i_{1d}$

$\phi_q = -\left(L_{aq} + L_l\right) i_q + L_{aq} i_{1q} + L_{aq} i_{2q}$

The model used in this study is synchronous generator 3rd order model. Hence, it neglects the effect of damper winding. Therefore, i_{1d} , i_{1q} and i_{2q} can be ignored. Hence re writing those equation for 3rd order model it becomes,

$\phi_d = -L_d i_d + L_{ad} i_{fd}$ ………………………… (9)

$\phi_q = -L_q i_q$ …………………………………… (10)

Where,
$L_d = L_{ad} + L_l$

$L_q = L_{aq} + L_l$

From equation (9),

$i_{fd} = \frac{\phi_d + L_d i_d}{L_{ad}}$ … … … … … … … … … … … … … … . . … (11)

Substituting ϕ_d in terms of v_q and i_q from equation (8)

$\phi_d = \frac{v_q + R_a i_q}{w_r}$, Then substitue ϕ_d to above i_{fd} equation (11)

$$i_{fd} = \frac{v_q + R_a i_q + w_r L_d i_d}{w_r L_{ad}}$$

Replace the $X = \omega L$ by the corresponding reactance X,

$$i_{fd} = \frac{v_q + R_a i_q + X_d i_d}{X_{ad}}$$

In 3rd order model, Stator winding resistance is neglected. Hence above equation can rewrite solving v_q,

$$v_q = i_{fd} X_{ad} - X_d i_d$$

From the phasor diagram above figure 9. It can show that,

$V_q = v_q + X_e i_d$; substitute v_q here, it can prove,

$V_q = i_{fd} X_{ad} + X_d i_d - X_e i_d$

$V_q = i_{fd} X_{ad} - (X_d - X_e) i_d$ … … … … … … … … … … … … … …(12)

With the pu $w_r = 1$, the equation(8) becomes,

$v_q = \phi_d - R_a i_q$ …………………………………………..(13)

Rotor flux linkage can be written as [9],

$$\phi_{fd} = L_{ffd} i_{fd} + L_{f1d} i_{1d} - L_{ad} i_d$$

In synchronous generator 3rd order model, it is neglected the effect of damper winding. Hence

$\phi_{fd} = L_{ffd} i_{fd} - L_{ad} i_d$ ………………………….……….(14)

Multiply the equation (14) by $\frac{L_{ad}}{L_{ffd}}$

$\phi_{fd} * \frac{L_{ad}}{L_{ffd}} = L_{ad} i_{fd} - \frac{L_{ad}^2}{L_{ffd}} i_d$ ……………………………………….(15)

Some of the above terms can be expressed as,

$E_I = L_{ad} i_{fd};$ voltage propotional to i_{fd} ………………….….….(16)

$$e_q' = \frac{L_{ad}}{L_{ffd}} \phi_{fd};\ \text{voltage propotional to } \phi_{fd}$$

Hence equation (15) can be written as of the terms of new definitions,

$e_q' = E_I - \frac{L_{ad}^2}{L_{ffd}} i_d$…………………………………….……….(17)

Neglecting the damper winding constants L_d' can be expressed as [9],

$L_d' = L_d \left(\frac{T_d'}{T_{d0}'}\right)$ …………………………………………………...(18)

Where,

$T_d' = \frac{1}{R_{fd}} \left(L_{fd} + \frac{L_{ad} L_l}{L_{ad} + L_l}\right)$ [9]

$T_{d0}' = \frac{L_{ad} + L_{fd}}{R_{fd}}$ [9]

Substituting T_d' *and* T_{d0}' *to equation* (18), it can derive,

$L_d' = L_l + \frac{L_{ad} L_{fd}}{L_{ad} + L_{fd}}$

$L_l = L_d - L_{ad}$

Substituting L_l *to above* L_d',

$L_d' = L_d - L_{ad} + \frac{L_{ad} L_{fd}}{L_{ad} + L_{fd}}$

$= L_d - \frac{L_{ad}^2}{L_{ad} + L_{fd}}$

$L_{ffd} = L_{ad} + L_{fd}$

Therefore, $L_d' = L_d - \frac{L_{ad}^2}{L_{ffd}}$

$L_d - L_d' = \frac{L_{ad}^2}{L_{ffd}}$ ………………………………….…(19)

Substitute $\frac{L_{ad}^2}{L_{ffd}}$ $in\ equation$ (17) it can derive,

$e_q' = E_I - (L_d - L'_d)i_d$ …………………………… (20)

In per unit base $X_d = L_d$, therefore from equation (9), (13) and (16),

$v_q = \phi_d - R_a i_q$

$= -X_d i_d + X_{ad} i_{fd} - R_a i_q$

$= -X_d i_d + E_I - R_a i_q$

$E_I = v_q + X_d i_d + R_a i_q$

Substitute E_I $in\ equation$ (20), it derives,

$e_q' = v_q + X_d i_d + R_a i_q - (X_d - X_d')i_d$

$e_q' = v_q + X_d' i_d + R_a i_q$,

In the 3rd order model, we neglect the stator resistance, therefore,

$$i_d = \frac{e_q' - v_q}{X_d'}$$

The stator voltage for v_d can be written as [9]

$$v_d = \frac{d\Phi_d}{dt} - \phi_q w_r - R_a i_d$$

Under the steady state condition , above equation gives,

$v_d = -\phi_q w_r - R_a i_d$

$= L_q w_r i_q - R_a i_d$

$= X_q i_q - R_a i_d$

Neglecting Stator resistance for 3rd order model, it can derive,

$$i_q = \frac{v_d}{X_q}$$

Substitute equation (4) and (5) in equation (1) and (2), we get

$P \ = V_t i_q \cos\delta + V_t i_d \sin\delta$ … … … … … … … … … … … … … . . (21)

$Q \ = V_t i_d \sin\delta - V_t i_q \cos\delta$ ……………………………….(22)

$Solving\ above\ equation\ for\ i_d\ and\ i_q,$

$$i_d = \frac{Qcos\delta + Psin\delta}{V_t} \text{ ……………………………………………(23)}$$

$$i_q = \frac{Pcos\delta - Qsin\delta}{V_t} \text{……………………………………………..(24)}$$

Substitute equation (6) and (12) in equation (1),

$$P = V_d i_d + V_q i_q$$

$$= (X_q - X_e)\, i_q\, i_d + [-(X_d - X_e)\, i_d + X_{ad}\, i_{fd}]\, i_q$$

$$= X_{ad}\, i_{fd} i_q + i_q\, i_d\, (X_q - X_d) \text{ …………………………..(25)}$$

Substitute equation (23) and (24) in equation (25), it can derive,

$$P = X_{ad} \frac{(Pcos\delta - Qsin\delta) i_f}{V_t} + \left(X_q - X_d\right) \frac{PQ\left(1 - 2sin^2\delta\right) + \left(P^2 - Q^2\right) sin\delta cos\delta}{{V_t}^2} \text{ ……………………….(26)}$$

Generator terminal voltage can express as,

$$V_t = \sqrt{V_d^2 + V_q^2}$$

$$V_t^2 = V_d^2 + V_q^2 \text{ ……………………………………………………………,…………….(27)}$$

Substitute equation (6) and (12) in (27), it can derive

$$= X_q^2 i_q^2 + i_d^2 X_d^2 - 2X_d\, X_{ad} i_f i_d + X_{ad}^2 i_f^2 \text{ ……………………………………………..(28)}$$

Substitute equation (23) and (24) in (28),

$$V_t^2 = X_q^2 \left(\frac{Pcos\delta - Qsin\delta}{V_t}\right)^2 + X_{ad}^2 i_f^2 + X_d^2 \left(\frac{Qcos\delta + Psin\delta}{V_t}\right)^2 - 2X_{ad} X_d\, i_f \left(\frac{Qcos\delta + Psin\delta}{V_t}\right) \text{..(29)}$$

Only unknown parameters of the (26) and (29) are $X_d, X_q\ and\ X_{ad}$. Using mathematical estimation method these unknown parameters can be estimated.

3.2 Derivation of Mathematical function to estimate dynamic parameters, X'_d and T'_{d0}

The field voltage and field current is related in dynamic conditions are as follows,

$$V_f = R_f i_f + \frac{d\phi_f}{dt} \quad \text{..(30)}$$

$$\phi_f = L_{ffd} i_{fd} + L_{fkd} i_{kd} - L_{afd} i_d$$

In 3rd order model, the effect of damper windings is neglected. Hence it can derive,

$$\phi_f = L_{ffd} i_{fd} - L_{afd} i_d$$

In L_{ad} base per unit system, it is derived that,

$L_{afd} = L_{ad}$ Then,

$$\phi_f = L_{ffd} i_{fd} - L_{ad} i_d$$

In pu base X=L. Therefore,

$$\phi_f = X_{fd} i_{fd} - X_{ad} i_d \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (31)$$

Substitute equation (31) in equation (30) it can derive.,

$$V_f = R_f i_f + X_f \frac{di_f}{dt} - X_{ad} \frac{di_d}{dt} \quad \text{.................................(32)}$$

In equation (32), other than the R_f and X_f all other parameters are measurable.X_{ad} has been already estimated from equation (26) and (29).

It is derived in equation (19),

$L_d - L'_d = \frac{L_{ad}^2}{L_{ffd}}$, In per unit system same equation can be written as,

$$X_d - X'_d = \frac{X_{ad}^2}{X_f}$$

$$X'_d = X_d - \frac{X_{ad}^2}{X_f} \quad \text{...(33)}$$

Once the X_f is known , X'_d can be calculated using equation (33).

The time constants T'_{d0}, T''_{d0}, T'_d and T''_d are major d axis time constants of the machine. The relationship of these time constant with the generator parameters are related as follows [9],

$(1+sT'_{d0})(1 + sT''_{d0}) = (1 + sT_1)(1 + sT_3)$ and ....(34)

$(1+sT'_d)(1 + sT''_d) = (1 + sT_4)(1 + sT_6)$ .... (35)

Where,

$T_1 = \frac{L_{ad}+L_{fd}}{R_{fd}}$

$T_2 = \frac{L_{ad}+L_{1d}}{R_{1d}}$

$T_3 = \frac{1}{R_{1d}}\left(L_{1d} + \frac{L_{ad}\,L_{fd}}{L_{ad}+L_{fd}}\right)$

$T_4 = \frac{1}{R_{fd}}\left(L_{fd} + \frac{L_{ad}\,L_{l}}{L_{ad}+L_{l}}\right)$

$T_5 = \frac{1}{R_{1d}}\left(L_{1d} + \frac{L_{ad}\,L_{l}}{L_{ad}+L_{l}}\right)$

$T_6 = \frac{1}{R_{1d}}\left(L_{1d} + \frac{L_{ad}L_{fd}\,L_{l}}{L_{ad}L_{l}+L_{ad}L_{fd}+L_{fd}L_{l}}\right)$

From the equation (34) and (35) following approximation can be obtained,

$T'_{d0} \approx T_1$

$T''_{d0} \approx T_3$

$T'_{d} \approx T_4$

$T''_{d} \approx T_6$

In 3rd order model and damper winding constant are neglected, Hence the parameters we can estimate is limited to transient constants.

Therefore,

$$T'_{d0} = \frac{L_{ad} + L_{fd}}{R_{fd}}$$

$$L_{ad} + L_{fd} = L_{ffd}$$

$$L_{ffd} = X_f/\omega$$

$$T'_{d0} = \frac{X_f}{\omega R_{fd}} \cong \frac{X_f}{\omega_0 R_{fd}} \quad \text{.....................................} \quad (36)$$

Therefore, once the X_f and R_f is calculated using the equation (32) , one can calculate the X'_d and T'_{d0} using equations (33) and (36).

3.3 Apply Levenberg Marquardt NLS algorithm to derived equations to estimate unknown parameters

This study is focused on estimating the synchronous generator parameters of X_d, X_q, X_{ad}, X_f and R_f.

In order to apply the derived equations to NLS algorithm, two equations (26) and (29) will work as one system and equation (32) will work as another system.

By applying two equation functions (26) and (29) in the NLS algorithm, it will estimate X_d, X_q and X_{ad} and applying (32) to the NLS algorithm it will estimate X_f and R_f.

Levenberg Marquart method applied in MATLAB is shown in figure 10 as a flowchart.

Levenberg – Marquardt Method implemented in MATLAB in flowchart,

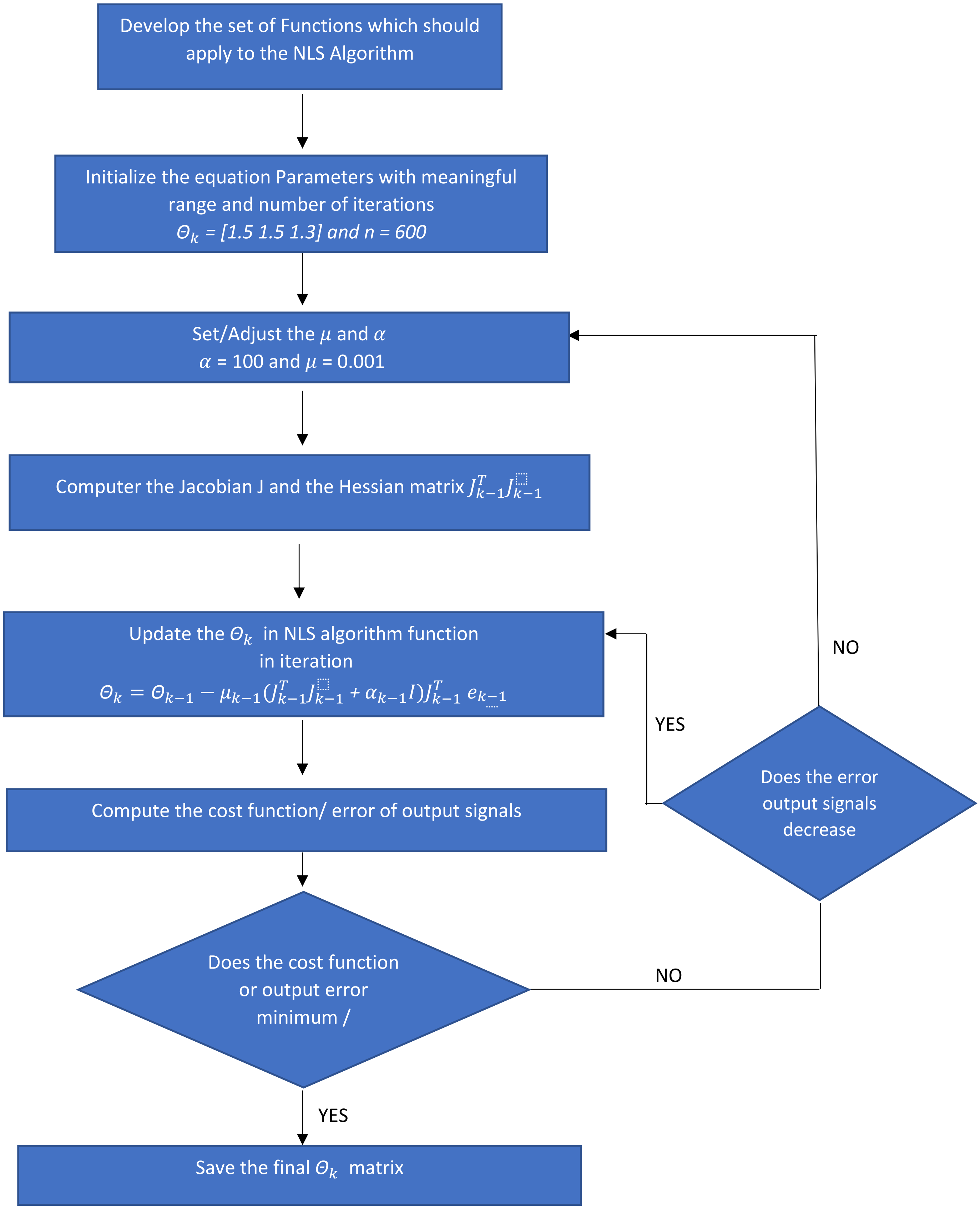

Figure 10: Levenberg – Marquardt Method implemented in MATLAB

3.3.1 Estimation of X_d, X_q and X_{ad}

In this case, set of unknown parameters are,

$$\Theta = \begin{bmatrix} X_d \\ X_q \\ X_{ad} \end{bmatrix}$$

Two functional equations which apply for the algorithm are as follows,

$$y_1 = X_{ad}\frac{(Pcos\delta - Qsin\delta)i_f}{V_t} + \left(X_q - X_d\right)\frac{PQ(1-2sin^2\delta) + (P^2-Q^2)cos\delta sin\delta}{{V_t}^2} - P$$

$$y_2 = \sqrt{X_q^2(\frac{Pcos\delta - Qsin\delta}{V_t})^2 + X_{ad}^2 i_f^2 + X_d^2(\frac{Psin\delta + Qcos\delta}{V_t})^2 - 2X_d\, X_{ad} i_f(\frac{Psin\delta + Qcos\delta}{V_t})} - V_t$$

The Jacobian matrix of for the two functions can be written as follows,

$$J^T = \begin{bmatrix} \frac{\partial y_1(1)}{\partial X_d} & \cdots \frac{\partial y_1(N)}{\partial X_d} & \frac{\partial y_2(1)}{\partial X_d}\cdots & \frac{\partial y_2(N)}{\partial X_d} \\ \frac{\partial y_1(1)}{\partial X_q} & \frac{\partial y_1(N)}{\partial X_q} & \frac{\partial y_2(1)}{\partial X_q} & \frac{\partial y_2(N)}{\partial X_q} \\ \frac{\partial y_1(1)}{\partial X_{ad}} & \cdots \frac{\partial y_1(N)}{\partial X_{ad}} & \frac{\partial y_2(1)}{\partial X_{ad}}\cdots & \frac{\partial y_2(N)}{\partial X_{ad}} \end{bmatrix}$$

Here,

$$\frac{\partial y_1}{\partial X_d} = \frac{-(\cos\delta\sin\delta(P^2 - Q^2) - PQ(2\sin^2\delta - 1)}{V_t^2}$$

$$\frac{\partial y_1}{\partial X_q} = \frac{(\cos\delta\sin\delta(P^2 - Q^2) - PQ(2\sin^2\delta - 1)}{V_t^2}$$

$$\frac{\partial y_1}{\partial X_{ad}} = \frac{I_{fd}*(P\cos\delta - Q\sin\delta)}{V_t}$$

$$\frac{\partial y_2}{\partial X_d} = \frac{\frac{2X_d(Q\cos\delta + P\sin\delta)^2}{V_t^2} - \frac{2I_{fd}X_{ad}(Q\cos\delta + P\sin\delta)}{V_t}}{2\sqrt{I_{fd}^2X_{ad}^2 + \frac{X_d^2(Q\cos\delta + P\sin\delta)^2}{V_t^2} + \frac{X_q^2(P\cos\delta - Q\sin\delta)^2}{V_t^2} - \frac{2I_{fd}X_{ad}X_d(Q\cos\delta + P\sin\delta)}{V_t}}}$$

$$\frac{\partial y_2}{\partial \mathrm{X}_q} = \frac{(\mathrm{X}_q(P\cos\delta - \mathrm{Q}\sin\delta)^2)}{V_t^2\sqrt{I_{fd}^2X_{ad}^2 + \frac{X_d^2(Q\cos\delta + \mathrm{P}\sin\delta)^2}{V_t^2} + \frac{X_q^2(P\cos\delta - \mathrm{Q}\sin\delta)^2}{V_t^2} - \frac{2I_{fd}\mathrm{X_{ad}}\mathrm{X_d}(Q\cos\delta + \mathrm{P}\sin\delta)}{V_t}}}$$

$$\frac{\partial y_2}{\partial \mathrm{X}_{ad}} = \frac{\frac{(2\mathrm{X_{ad}}I_{fd}^2 - (2\mathrm{X_d}(Q\cos\delta + \mathrm{P}\sin\delta)I_{fd}}{V_t}}{2\sqrt{I_{fd}^2X_{ad}^2 + \frac{X_d^2(Q\cos\delta + \mathrm{P}\sin\delta)^2}{V_t^2} + \frac{X_q^2(P\cos\delta - \mathrm{Q}\sin\delta)^2}{V_t^2} - \frac{2I_{fd}\mathrm{X_{ad}}\mathrm{X_d}(Q\cos\delta + \mathrm{P}\sin\delta)}{V_t}}}$$

All the variables mentioned above are measurable quantities and can be feed into the algorithm. All the data points of the measurements must be included into the Jacobian matrix. Once the Jacobian matrix is defined for all data points, it can feed into the Levenberg algorithm and conduct iteration for defined number of iterations until the cost function becomes minimum or the difference of the adjacent iteration output parameters become minimum or satisfactory.

3.3.2 Estimation of X_f and R_f

In derivation of X_f and R_f, the unknown parameter matrix becomes,

$$\Theta = \begin{bmatrix} \mathrm{X_f} \\ \mathrm{R_f} \end{bmatrix}$$

Here the functional equation to derive the Jacobian matrix is,

$$y_1 = R_f * i_f + X_f\frac{di_f}{dt} - X_{ad} * \frac{di_d}{dt} - V_f$$

The Jacobian matrix for above equation can be written as,

$$J^T = \begin{bmatrix} \frac{\partial y_1(1)}{\partial \mathrm{X_f}} & \cdots & \frac{\partial y_1(N)}{\partial \mathrm{X_f}} \\ \frac{\partial y_1(1)}{\partial \mathrm{R_f}} & \cdots & \frac{\partial y_1(N)}{\partial \mathrm{R_f}} \end{bmatrix}$$

Where,

$$\frac{\partial y_1}{\partial \mathrm{X_f}} = \frac{di_f}{dt}$$

$$\frac{\partial y_1}{\partial \mathrm{R_f}} = i_f$$

All the variables mentioned above are measurable quantities and can be feed into the NLS algorithm. All the data points of the measurements must be included into the Jacobian matrix. Once the Jacobian matrix is defined for all data points, it can feed into the Levenberg algorithm and conduct iteration for defined number of iterations until the cost function becomes minimum or the difference of the adjacent iteration output parameters become minimum or satisfactory.

Chapter Summary

This chapter proposed the methodology to estimate the synchronous generator parameters using online measurement by giving small step response to the field voltage input. Mathematical functions which represent relationship between the generator parameters and the field measurements are described. Method of applying the estimation technique to extract the parameter from the mathematical function is shown in this chapter.

4.0 IMPLEMENTATION OF PROPOSED METHOD, RESULTS AND VALIDATION

The proposed methodology has implemented in two case studies as follows,

1. Using example generator data taken from the [9] and simulate that machine in MATLAB Simulation environment.
2. Real experiment measurement taken from the Kelanitissa Combine Cycle Power Plant, Sri Lanka

4.1 MATLAB Simulink Simulation Study

Following machine with given design data is considered for the simulation studies. The step response was obtained by giving 5% step input to the AVR voltage reference point. Measurement noise of SNR ratio around 27dB is added to simulation to obtain a similar behavior to the real environment measurements. Generator terminal voltage and current, Reactive and Active Power, power factor, field voltage and current were considered as the field measurements.

Following are the specification of the simulated generator model,

- Capacity – 555MVA
- Generator Terminal voltage – 11.5kV
- Nominal line current – 13,351.2 A
- Rotor speed - 3600
- Frequency – 60Hz
- Round Rotor, 2 pole
- Field voltage –257.183 kV
- Field current – 2158 A
- X_d - 1.81 pu
- X_q- 1.76 pu
- X_{ad}- 1.66 pu
- X'_d - 0.3 pu
- T'_{d0}- 8 sec
- Excitation type - Static

Figure 10 shows the complete MATLAB Simulink model of the generator which has major components of synchronous generator block, excitation system with AVR block, governor block, step up excitation transformer with pi networks connected to system bus.

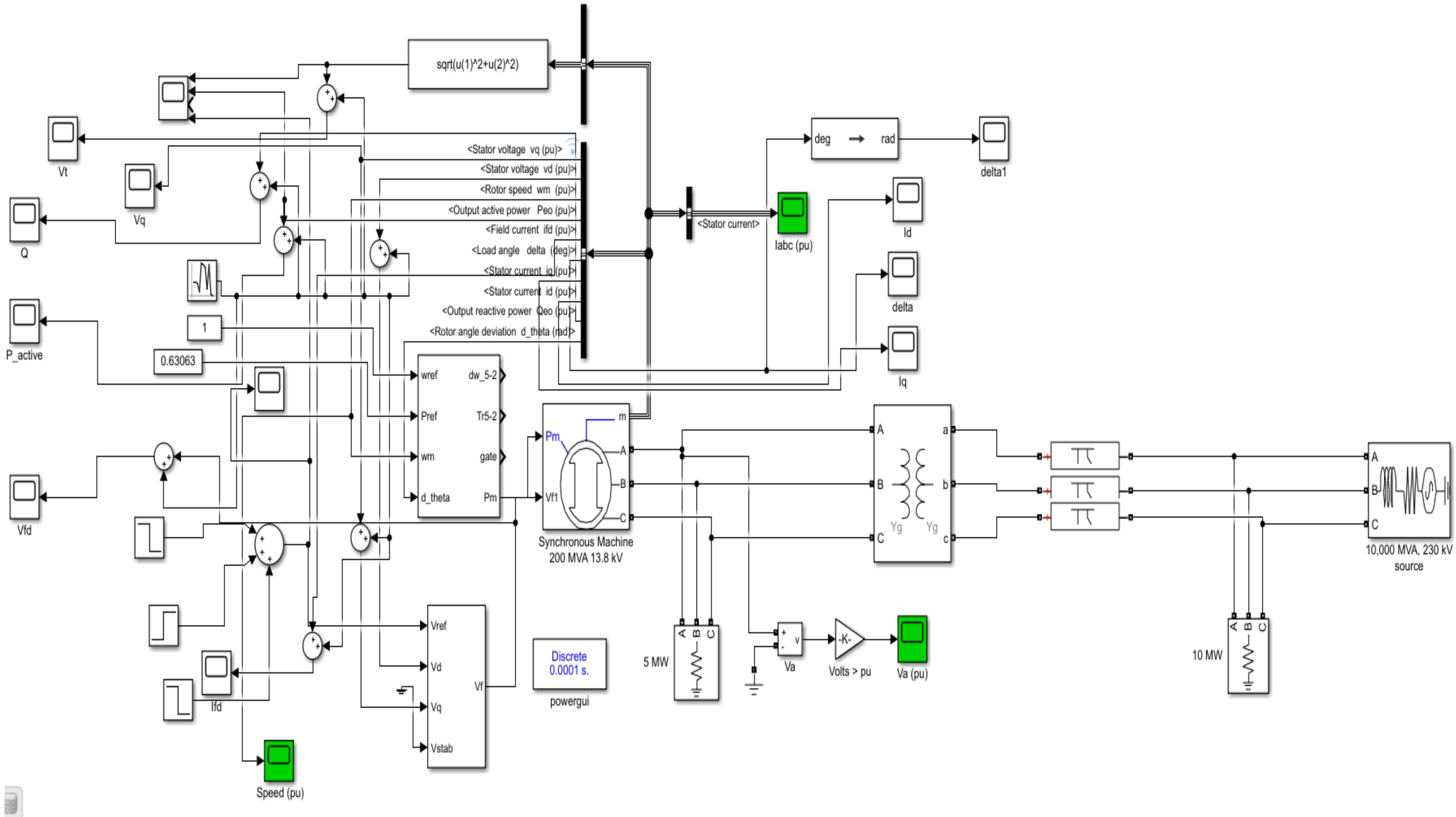

Figure 11 : MATLAB SIMULINK Model for Simulated Machine

Following are the results of MATLAB Simulink Simulation.

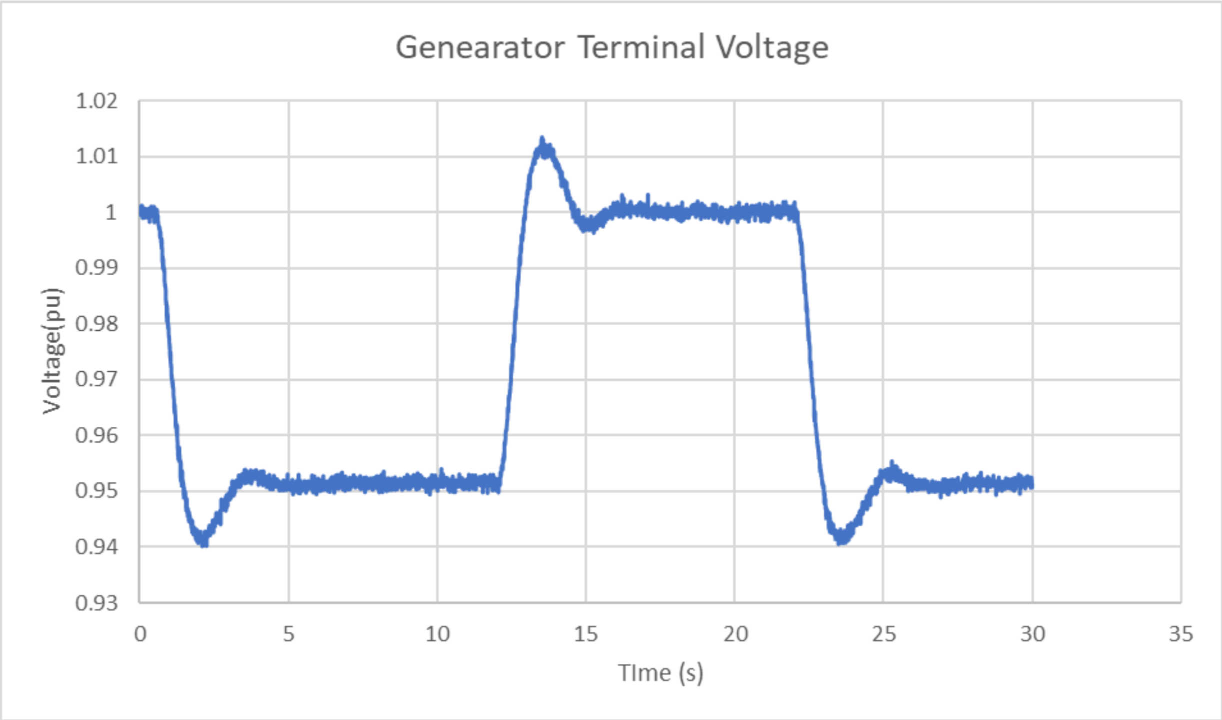

Figure 12: Generator Voltage: MATLAB Simulation

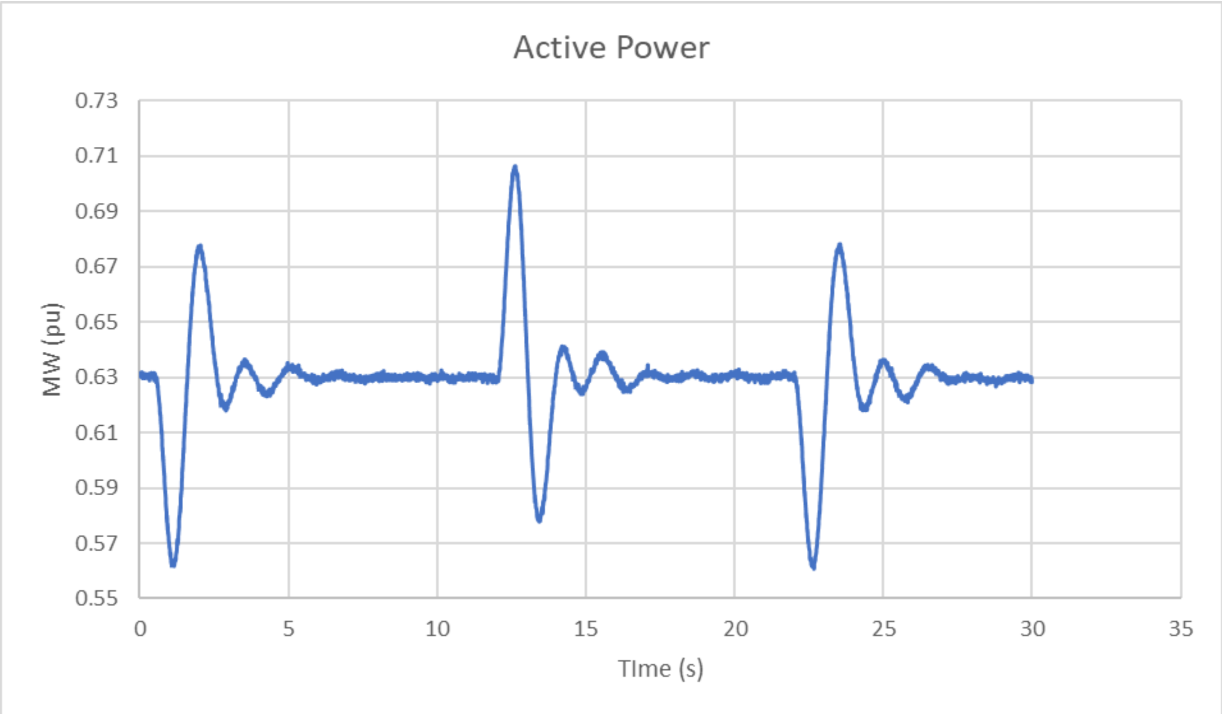

Figure 13: Active Power: MATLAB Simulation

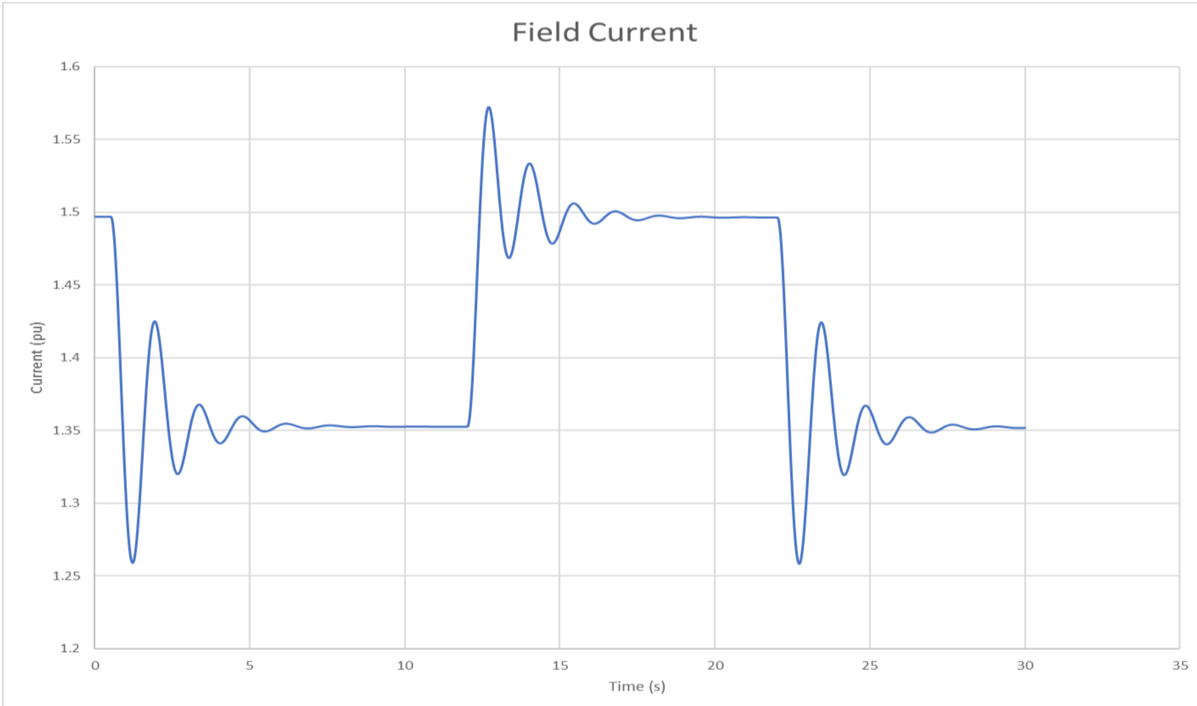

Figure 14: Field Current: MATLAB Simulation

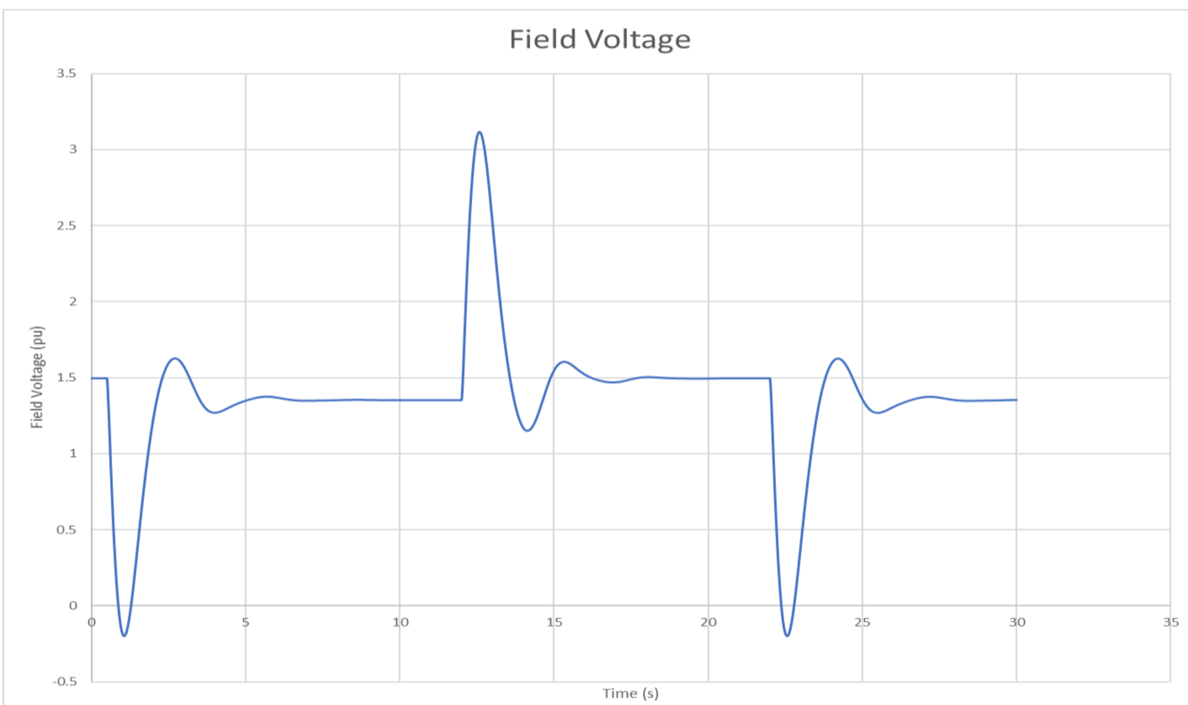

Figure 15: Field Voltage: MATLAB Simulation

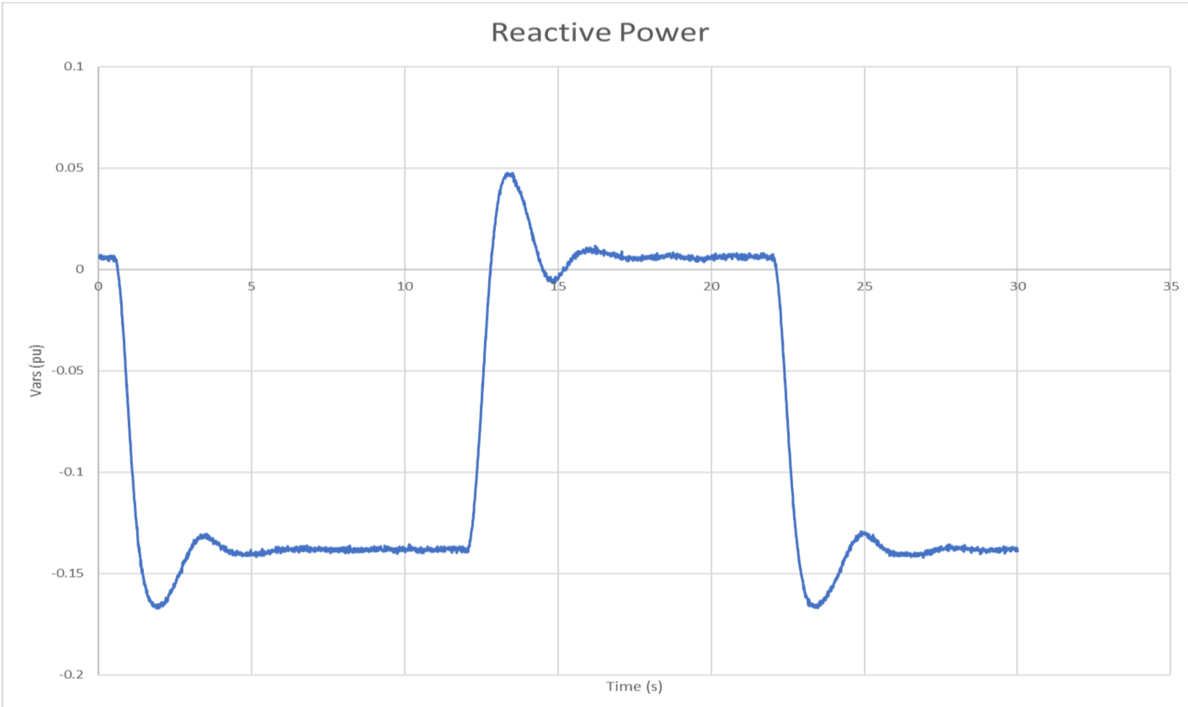

Figure 16: Reactive Power: MATLAB Simulation

Using the above measurements, NLS algorithm, Levenberg Marquart method was applied to estimate unknown parameters.

4.1.1 Estimation of X_d, X_q *and* X_{ad}

Using the parameter obtained in the MATLAB SIMULINK measurements, Nonlinear Least Square algorithm of Levenberg-Marquand is applied to identify the X_d, X_q *and* X_{ad} using the equation derived in (26) and (29). As the initial values for the algorithm, $X_d = 1.5$, $X_q = 1.5$ *and* $X_{ad} = 1.3$ were selected which are meaningful values for those parameters. For the Levenberg algorithm constants, μ_{k-1}=0.1 and α_{k-1}=100 was selected for the initial iteration.

Values are fed into the NLS algorithm and final results are listed in the table.

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X_d	1.81	1.7814	1.5
X_q	1.76	1.6928	3.8
X_{ad}	1.66	1.6314	1.7

Table 1 : Comparison of Actual Parameters and Estimated Parameters for X_d, X_q *and* X_{ad}

Following are the results of estimated parameters for complete iterations,

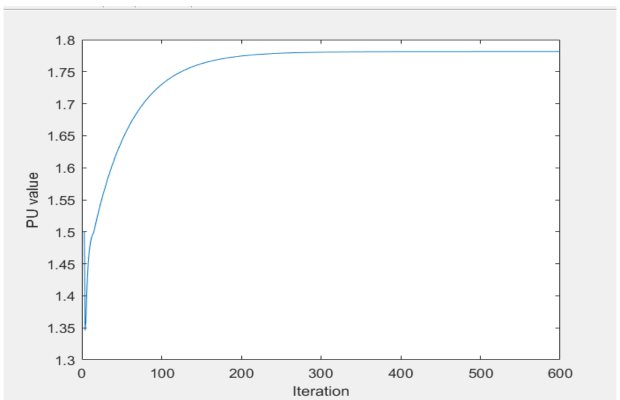

Figure 17 : Result of NLS for X_d

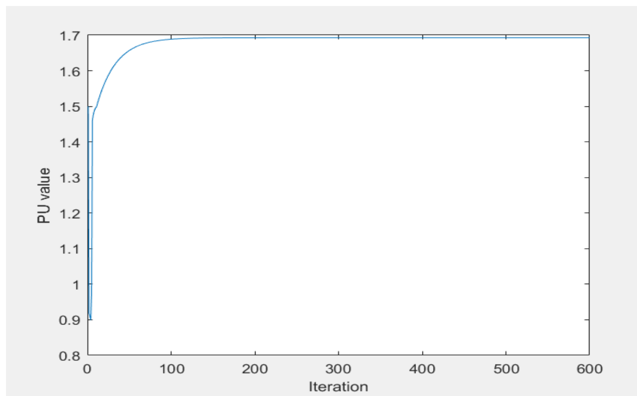

Figure 18 : Result of NLS for X_q

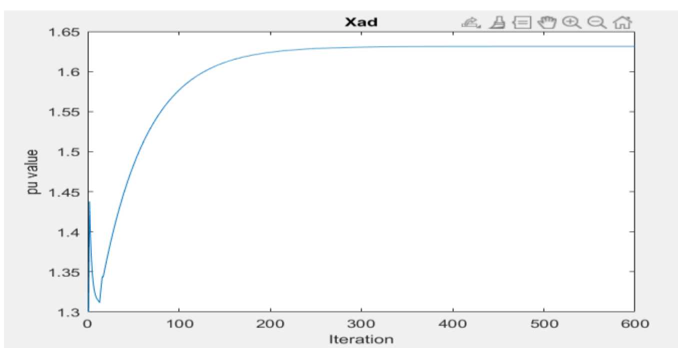

Figure 19 : Result of NLS for X_{ad}

In following simulation results, initial values are used for NLS as $X_d = 2.0$, $X_q = 2.0$ and $X_{ad} = 2.1$.Results proves that irrespective of the initial point of the iteration, the final results of the final iteration converge into the same value. It is important to select the initial iteration of a value which lies in meaningful range of the relevant parameter.

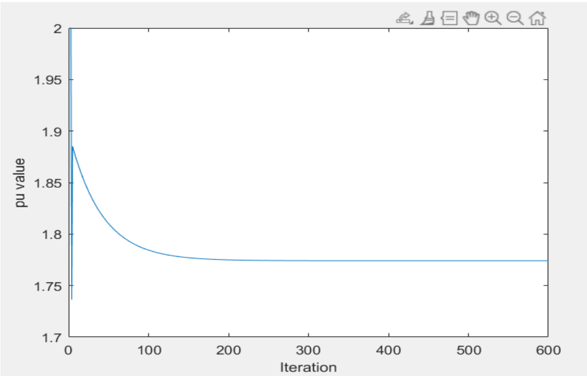

Figure 20: Result of NLS for X_d

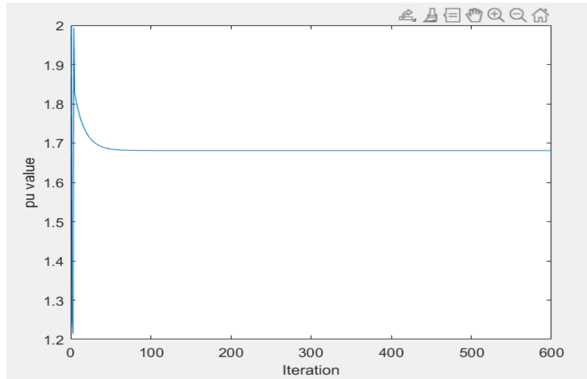

Figure 21: Result of NLS for X_q

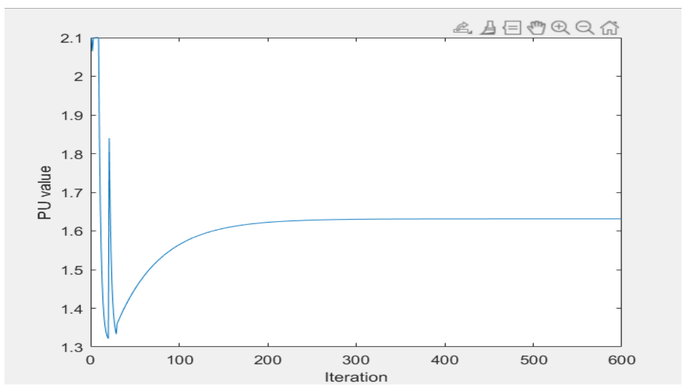

Figure 22: Result of NLS for X_{ad}

4.1.2 Estimation of X_f *and* R_f

As the next step, field parameters are estimated using the same NLS Levenberg Marquart algorithm using the equation (32). Field current and field voltage are available from the simulation measurement and hence the derivative of the same can be obtained by the measurement data.

Same as above, the initial parameters of X_f *and* $R_{f\_}$ were selected such as $X_f = 1.5\,pu\ and\ R_f =$ 0.0005 pu which are meaningful estimation to obtain the final results. For the Levenberg algorithm constants, μ_{k-1}=0.1 and α_{k-1}=100 was selected for the initial iteration.

Values are fed into the NLS algorithm and final results are listed in the following table.

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X_f	1.82	1.7923	1.5
R_f	0.000605	0.0006	0.84

Table 2: Comparison of Actual Parameters and Estimated Parameters for X_f and R_f

Following are the results of estimated parameters for complete iterations,

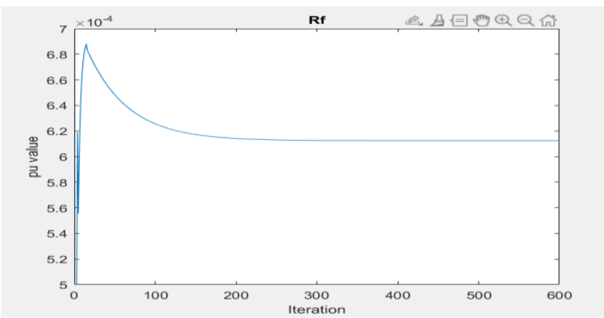

Figure 23: Result of NLS for R_f

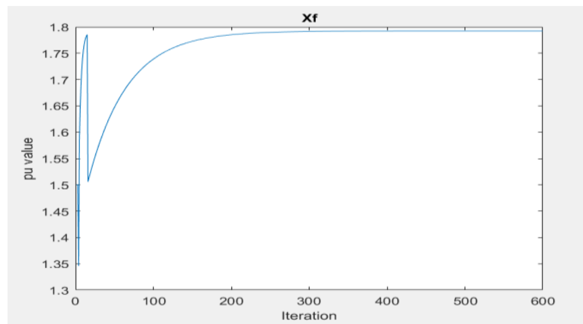

Figure 24: Results of NLS for X_f

Using the results of X_f *and* R_f, X'_d *and* T'_{d0} can be calculated using the equations (33) and (36) as follows,

$X'_d = X_d - \frac{X_{ad}^2}{X_f}$

$= 1.7814 - \frac{1.6314^2}{\mathbf{1.7923}}$

$= 0.2965$ pu

$T'_{d0} = \frac{X_f}{\omega R_{fd}} \cong \frac{X_f}{\omega_0 R_{fd}}$

$= \frac{1.7923}{2*\pi*50*0.0006}$

$= 7.9237$ sec

Comparison of the estimated results with the Machine design data are shown in following table.

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X'_d	0.3	0.2965	1.18
T'_{d0}	8 sec	7.9237 sec	0.95

Table 3: Comparison of Actual Parameters and Estimated Parameters for X'_d and T'_{d0}

4.2 Test conducted at Kelanitissa Combined Cycle Power Plant, Steam Turbine Generator.

In this section the proposed methodology is applied in real environment conditions. For that steam turbine (ST) generator of Kelanitissa Combine Cycle Power plant is selected. This plant consists of gas turbine and steam turbine which runs on combined cycle operation.

Details of the steam turbine generator is as follows.

<u>Generator ratings</u>

Type/Model No	Alstom T237- 268
Apparent power	75955 kVA
Nominal Stator Voltage	11500 V
Rated Frequency	50 Hz
Nominal Stator Current	3843A
Nominal Field Voltage	143V dc
Field resistance @ 20deg	0.0609 Ohm
Nominal Power Factor	0.8
Direct axis synchronous reactance	1.683
Transient Reactance	0.2193
Sub Transient reactance	0.1521
Nominal Field Current	1682A dc
Negative Sequence Reactance	0.160
Zero Sequence Reactance	0.081
Td0’	1.008 sec
Td0’’	0.037 sec
RPM	3000

Exciter machine data.

Rated power	241 kW
Rated field Voltage	21V dc
Rated field current	62A dc
Rectified Voltage	143V dc
Rectified Current	1682A dc
Rated Frequency	200 Hz
Stator Field winding resistance	4.4 ohm
Ceiling Voltage	33.5 V
Ceiling Current	100 A
RPM	3000
Cooling	Air
Number of Slots	54
Number of Poles	8
Number of Phases	9
Number of diodes	18

Following steps were conducted during the test

1. The Manufacture model of the AVR is GE EX2100E excitation system. Step response to the AVR is given by connecting to AVR software through the OEM GE software. Field voltage, and current, generator voltage, generator current, power factor, active power, step input signal to AVR and reactive power was recorded during the test. Sampling time of the recording is 10ms.

2. ST was Synchronized as per the normal operation guideline and loaded the machine to around 0.7pu, active power where it generates steady active power and no governor oscillation are visible.
    a. During the test, machine was operating at the active power of around 49MW and reactive power of around 0 MVar

3. Step response of 2% was given to the AVR voltage reference point through the AVR OEM software and kept it for 20 seconds and gave 2% step down input to bring back to original set point.

4. All the measurements mentioned in step 1 here is recorded and data was filtered with 50Hz LPF and the filtered data was used for further analysis. Since this oscillation lies between 2 to 10 Hz, selection of 50 Hz filter will give better response of the signals filtering out the measurement and environment noises.

In following figures, it shows the raw data and the filtered data.

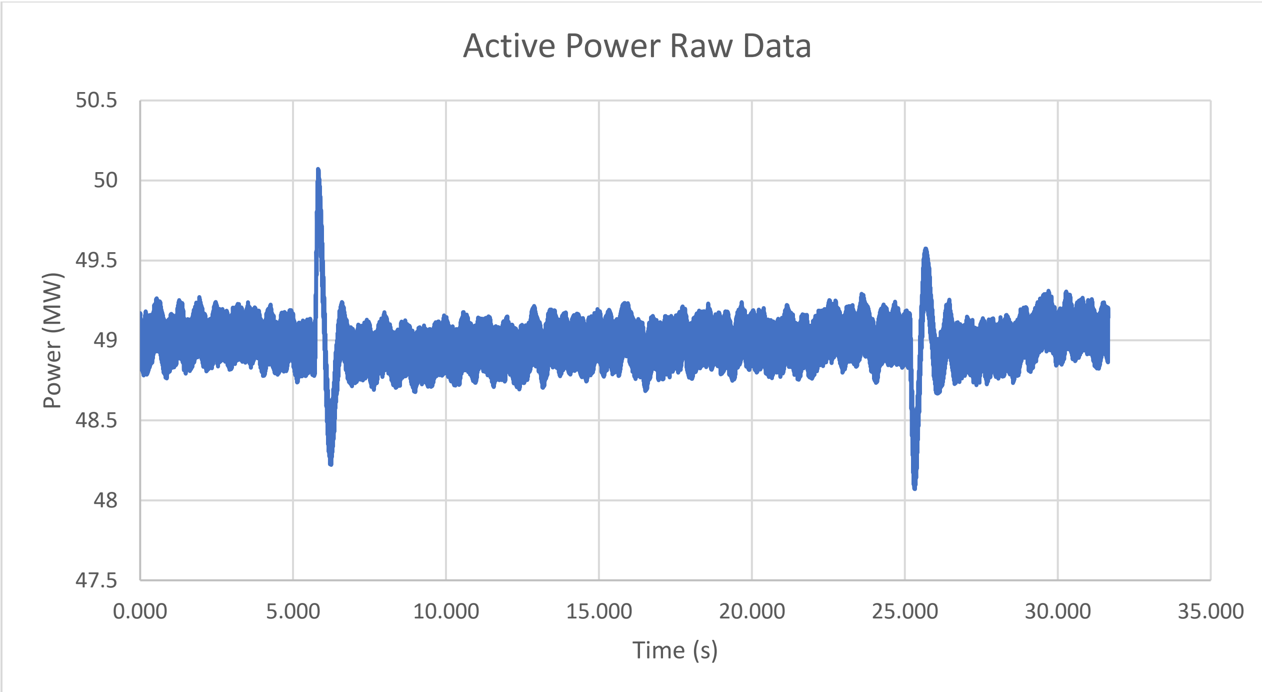

Figure 25: Active Power Measurement Raw Data: KCCP

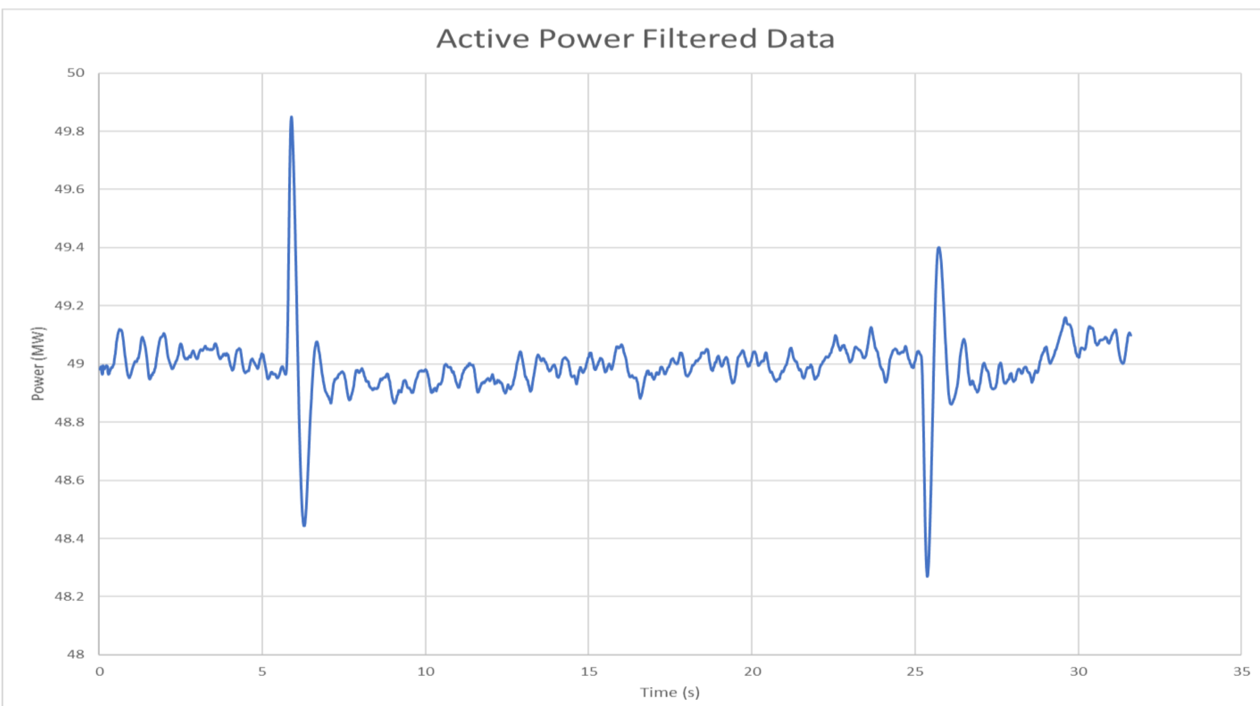

Figure 26: Active Power Measurement Filtered Data: KCCP

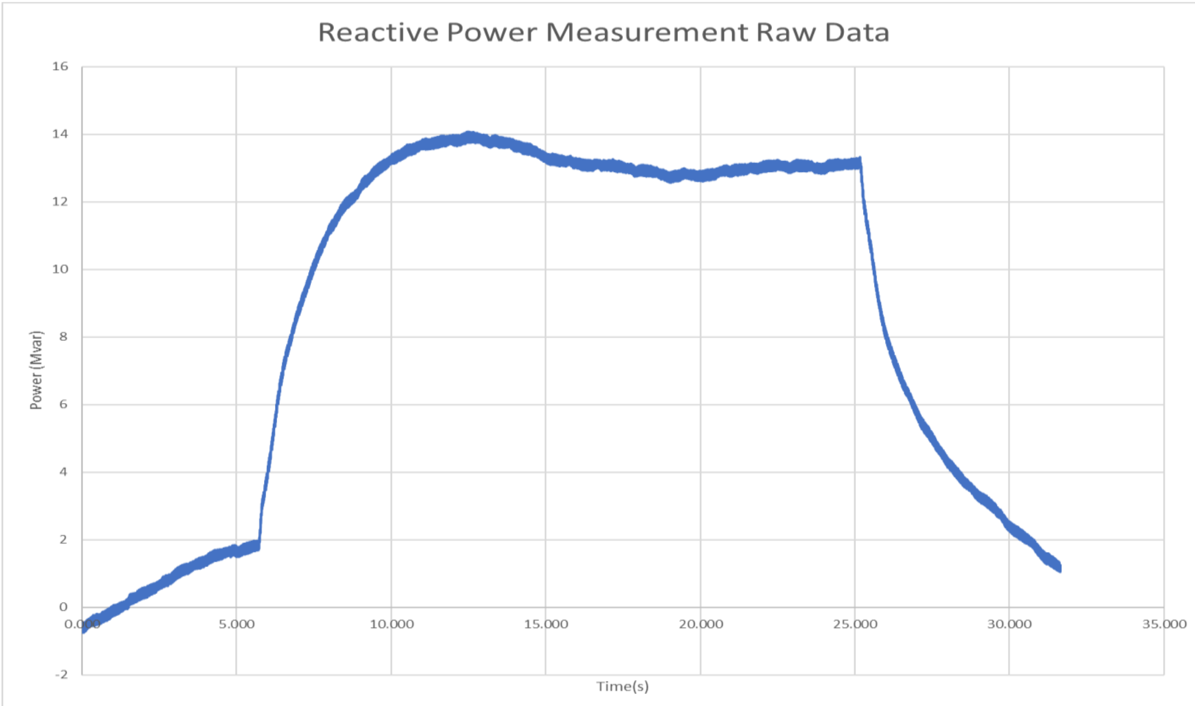

Figure 27: Reactive Power Measurement Raw Data: KCCP

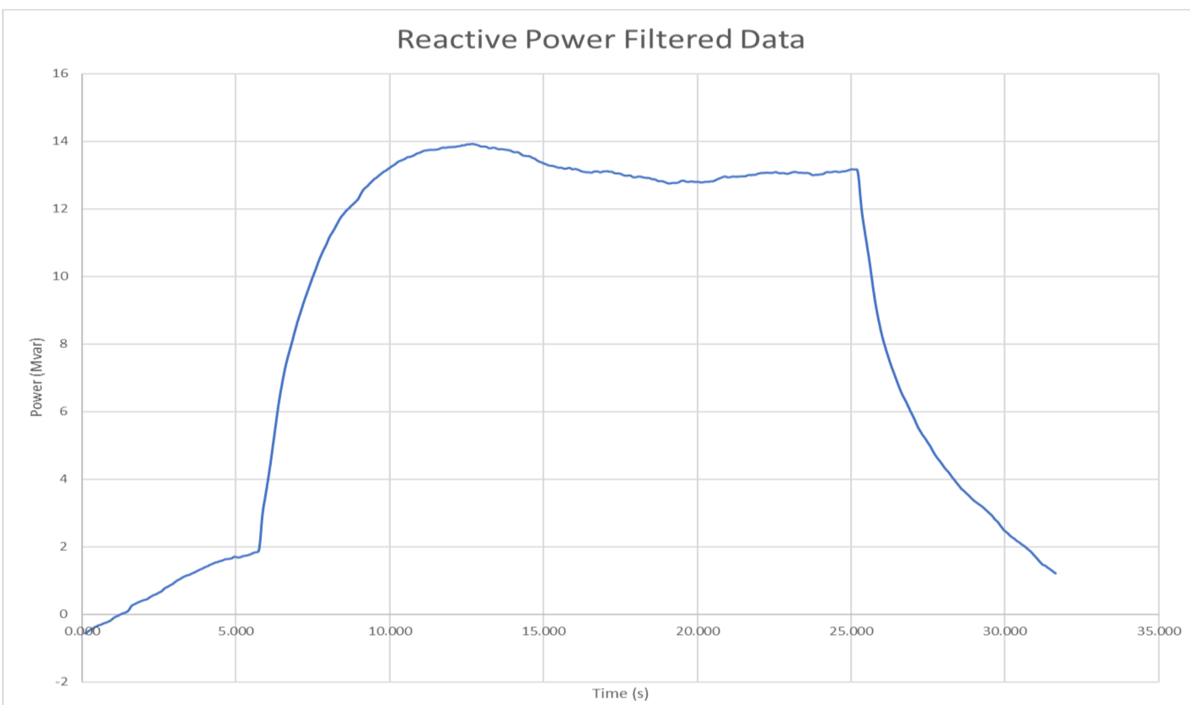

Figure 28: Reactive Power Measurement Filtered Data: KCCP

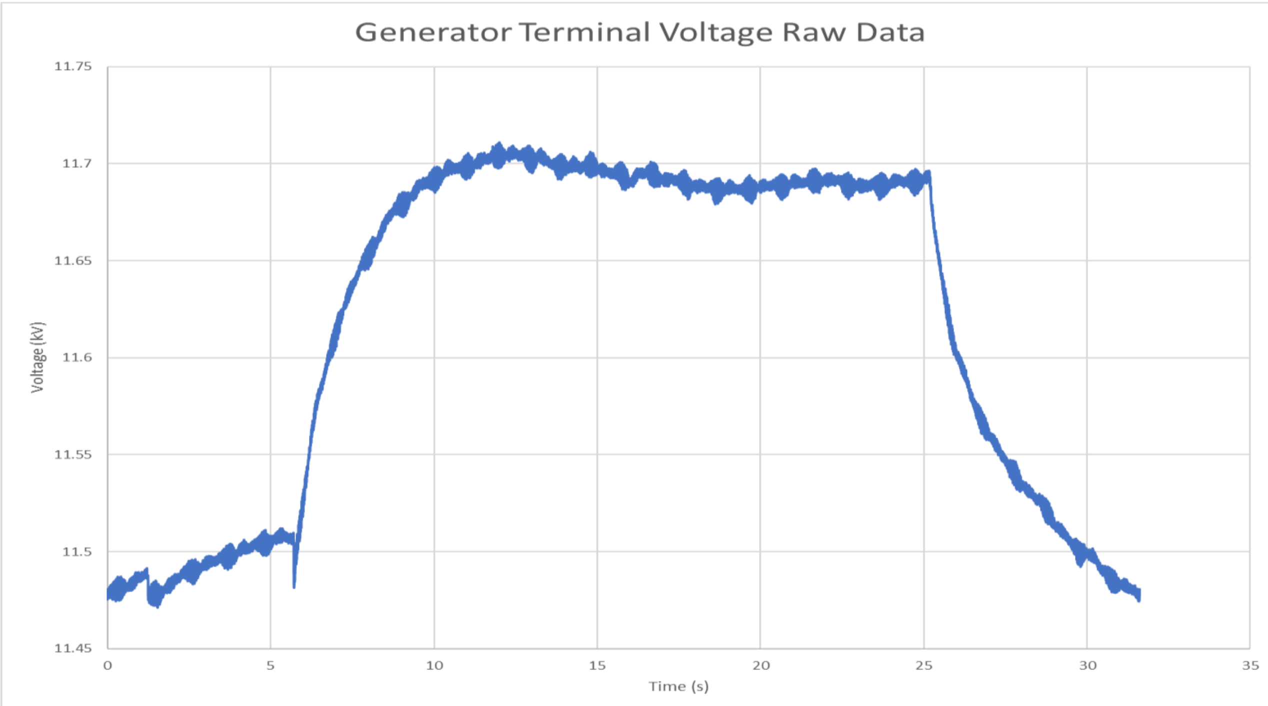

Figure 29: Generator Terminal Voltage Measurement Raw Data: KCCP

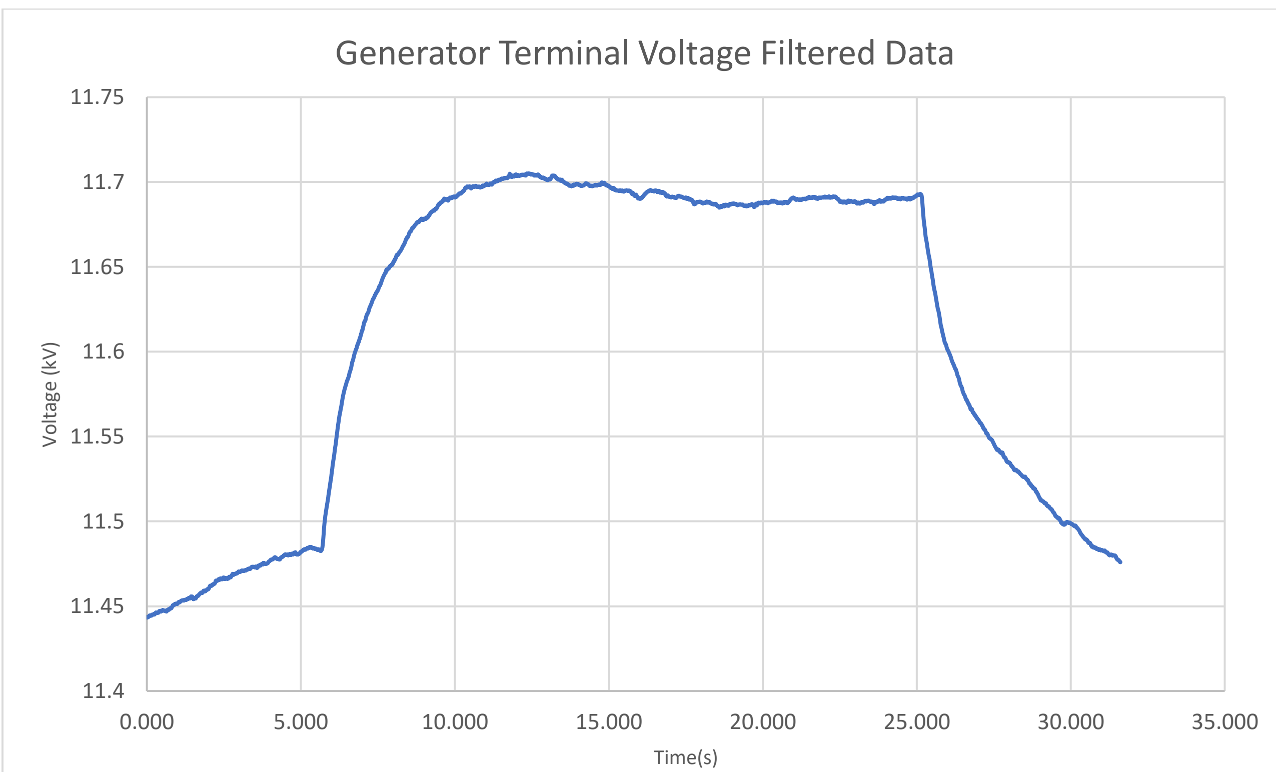

Figure 30: : Generator Terminal Voltage Measurement Filtered Data: KCCP

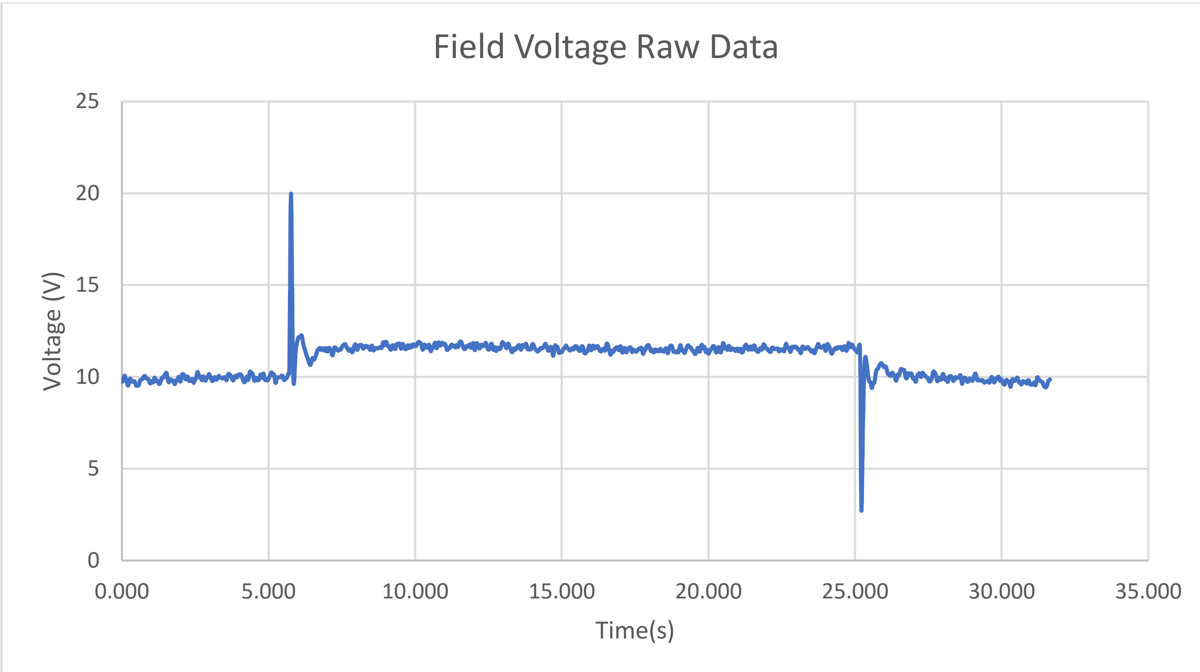

Figure 31: Field Voltage Measurement Raw Data: KCCP

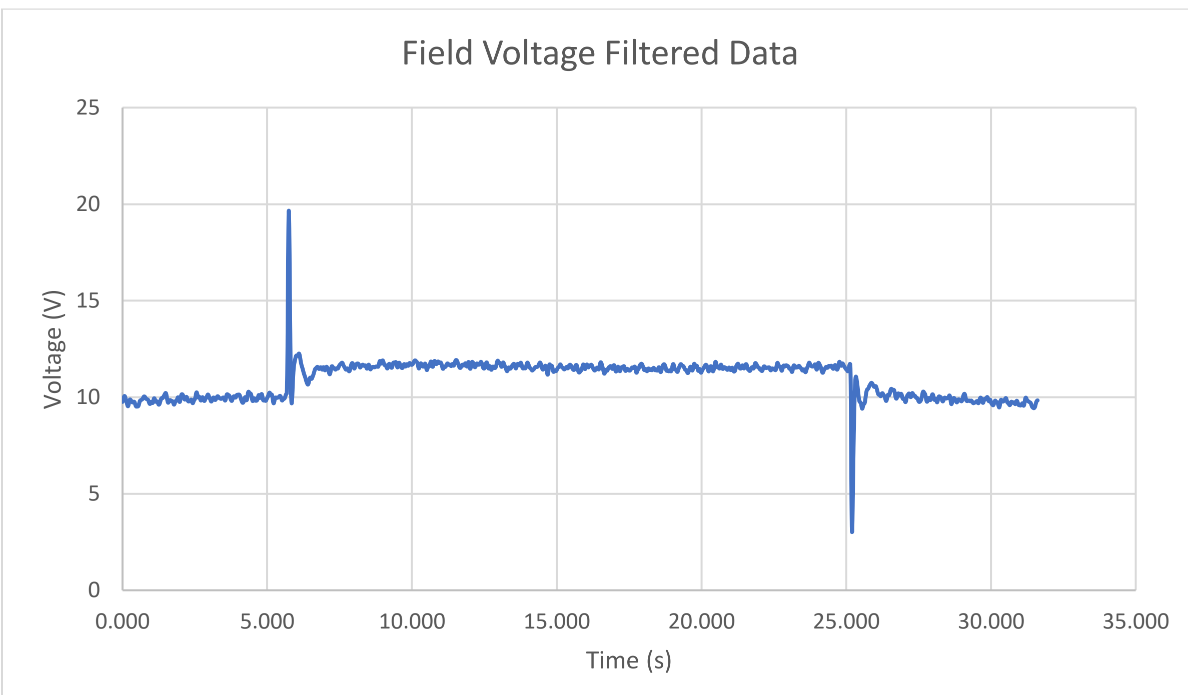

Figure 32: Field Voltage Measurement Filtered Data: KCCP

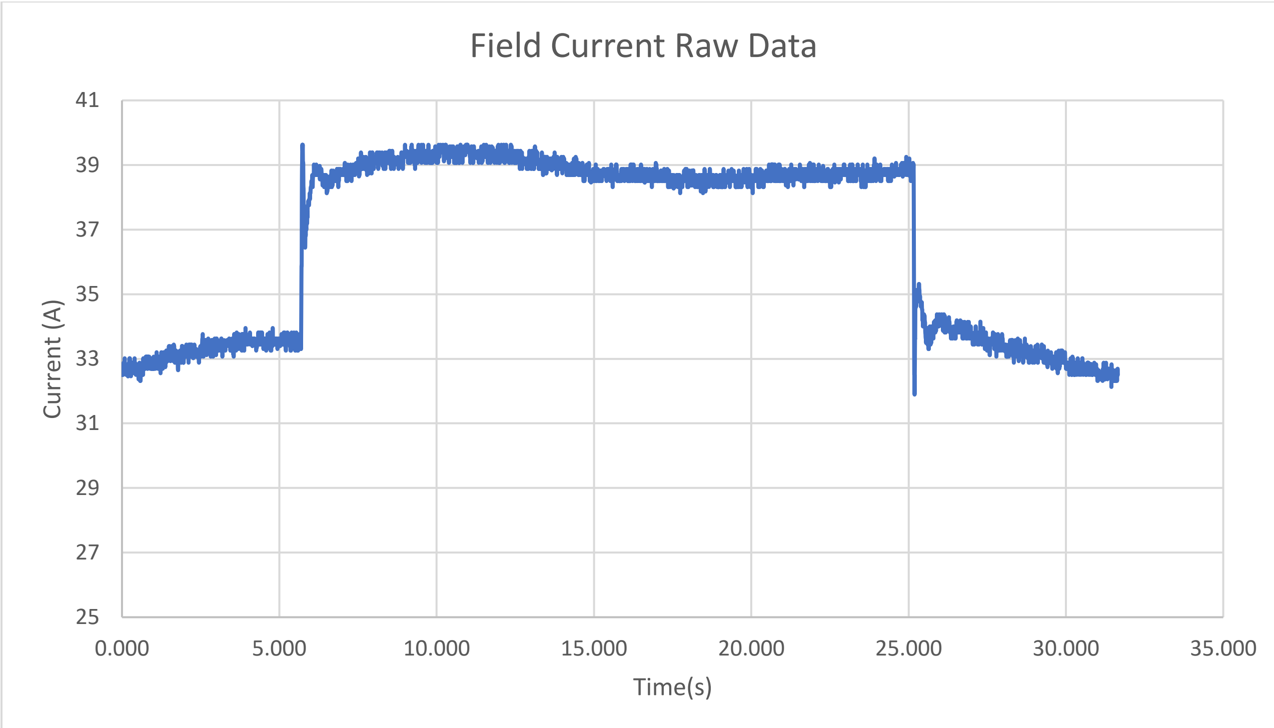

Figure 33: Field Current Measurement Raw Data: KCCP

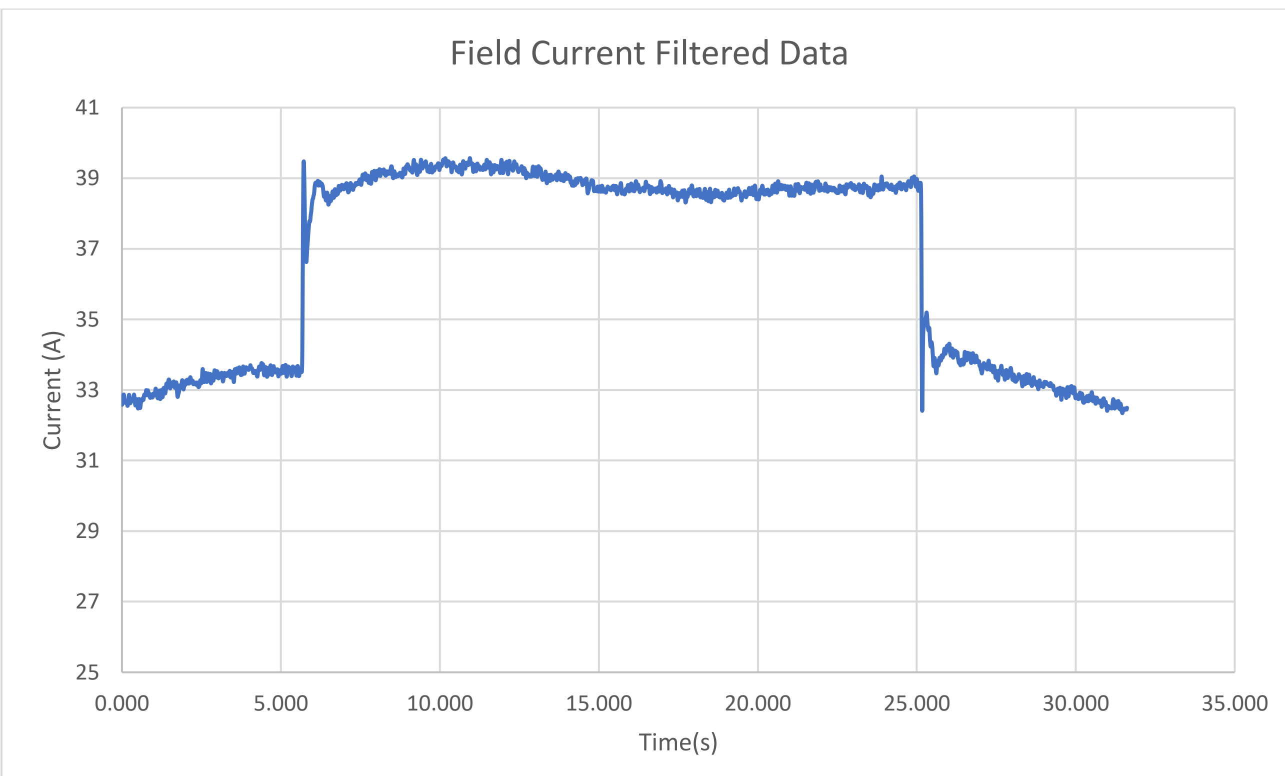

Figure 34 Field Current Measurement Filtered Data: KCCP

4.2.1 Estimation of X_d, X_q and X_{ad}

Using the data obtained in the real measurements, X_d, X_q and X_{ad} are estimated using the equation derived in (26) and (29) by applying it to Levenberg Marquardt algorithm. As the initial start for the algorithm, $X_d = 1.5$, $X_q = 1.5$ and $X_{ad} = 1.3$ were selected which are meaningful values for those parameters. For the Levenberg algorithm constants, μ_{k-1}=0.1 and α_{k-1}=100 was selected for the initial iteration.

Values are fed into the NLS algorithm and final results are listed in the table.

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X_d	1.683	1.6343	2.8
X_q	1.452	1.5156	4.3
X_{ad}	1.533	1.4409	6.0

Figure 35: Comparison of Actual and Estimated Parameters of X_d, X_q and X_{ad}

Following are the results of the estimation for the complete iterations,

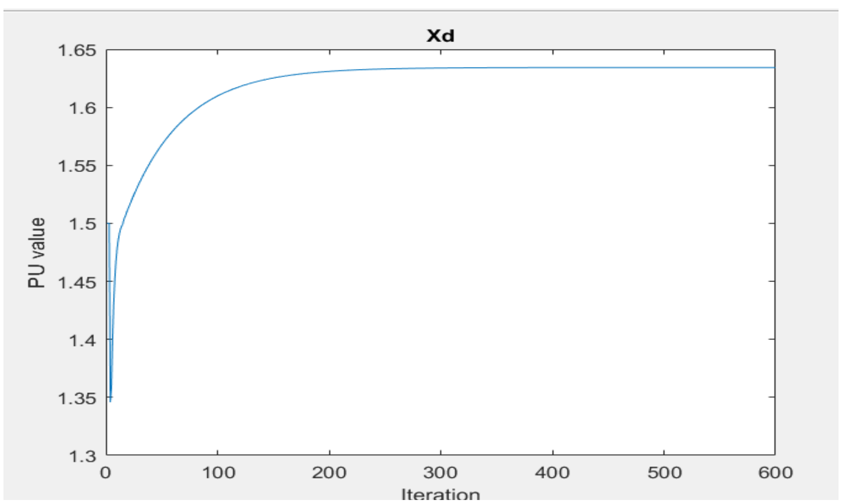

Figure 36: Results of NLS for X_d

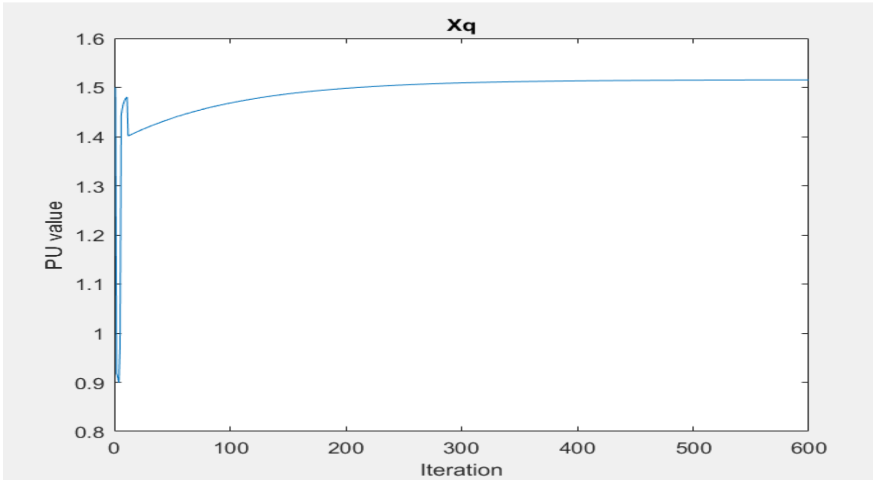

Figure 37: Results of NLS for X_q

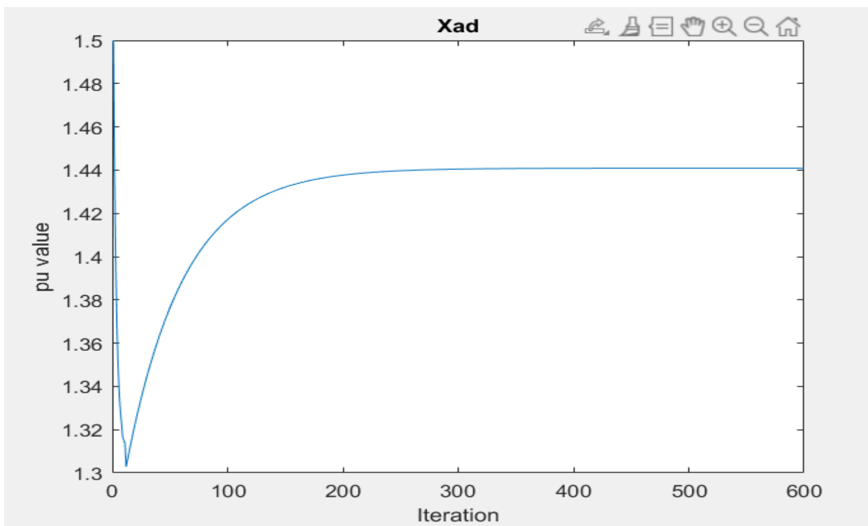

Figure 38: Results of NLS for X_{ad}

4.2.2 Estimation of X_f and R_f

The next step is to estimate field parameters using the same NLS Levenberg Marquart algorithm using the equation (32). The Field current and field voltage are available as the filed measurements and hence the derivative of the same is can be obtained by the measurement data.

Same as earlier, parameters of X_f and R_f were selected such as $X_f = 1.5pu$ and $R_f = 0.0005$ pu which are meaningful estimation to obtain the final results. For the Levenberg algorithm constants, μ_{k-1}=0.1 and α_{k-1}=100 was selected for the initial iteration.

Values are fed into the NLS algorithm and final results are listed in following table.

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X_f	1.6055	1.5127	5.7%
R_f	0.0051	0.004623	9.3%

Table 4 : Comparison of Actual and Estimated Parameters of X_f and R_f

Following are the results of the estimation for the complete iterations,

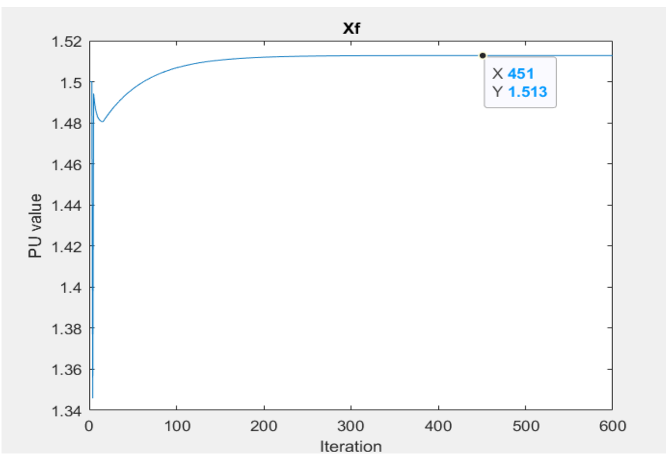

Figure 40 : Results of the NLS for X_f

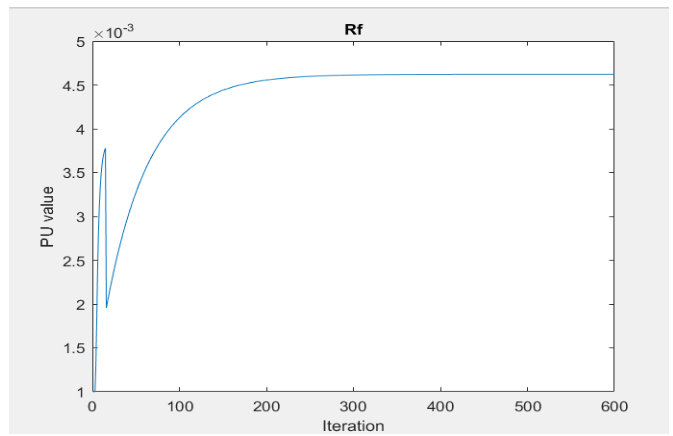

Figure 39: Results of NLS for R_f

Using the results of X_f *and* R_f and using the equations (33) and (36), X'_d *and* T'_{d0} can calculate as follows,

$$X'_d = X_d - \frac{X_{ad}^2}{X_f}$$

$$= 1.6343 - \frac{1.4409^2}{1.5127}$$

$$= 0.2618 \text{ pu}$$

$$T'_{d0} = \frac{X_f}{\omega R_{fd}} \cong \frac{X_f}{\omega_0 R_{fd}}$$

$$= \frac{1.5127}{2*\pi*50*0.004623}$$

$$= 1.0420 \text{ sec}$$

Comparison of the estimated results with the machine design data are shown in following table.

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X'_d	0.2193	0.2618	19.3%
T'_{d0}	1.008 sec	1.0420 sec	3.3%

Table 5: Comparison of Actual and Estimated Parameters of X'_d and T'_{d0}

4.3 Analysis and Validation of the MATLAB SIMULINK Simulation Results

Summary of the MATLAB SIMULINK Simulation results are as follows,

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X_d	1.81	1.7814	1.5
X_q	1.76	1.6928	3.8
X_{ad}	1.66	1.6314	1.8
X_f	1.82	1.7923	1.5
R_f	0.000605	0.0006	0.84
X'_d	0.3	0.2965	1.18
T'_{d0}	8 sec	7.9237 sec	0.95

To validate the results, estimated values were fed into the MATLAB SIMULINK simulation and obtained the same output signals.

Comparison the generator terminal voltage. active power and field voltage results for the actual generator parameters and the estimated parameters are as follows,

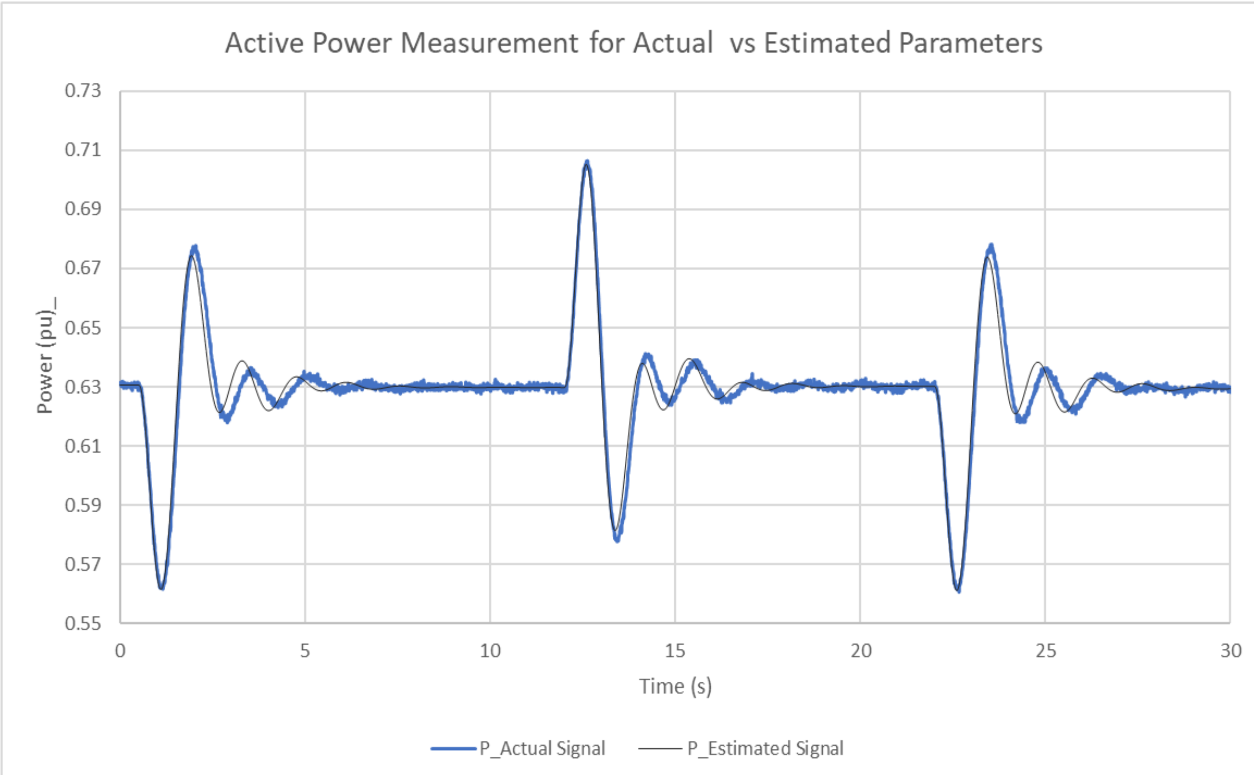

Figure 41: Active Power Measurement for Actual and Estimated Parameters

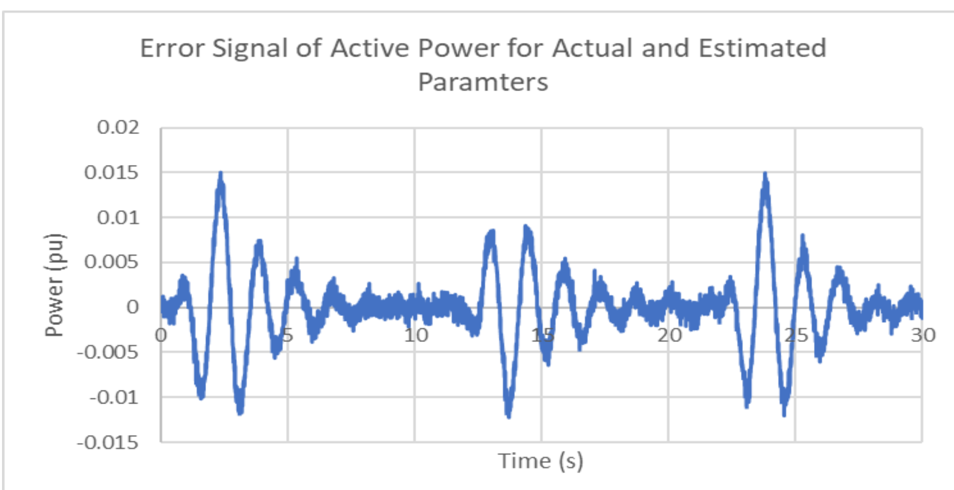

Figure 42: Error Signal of Active Power for Actual and Estimated Signal

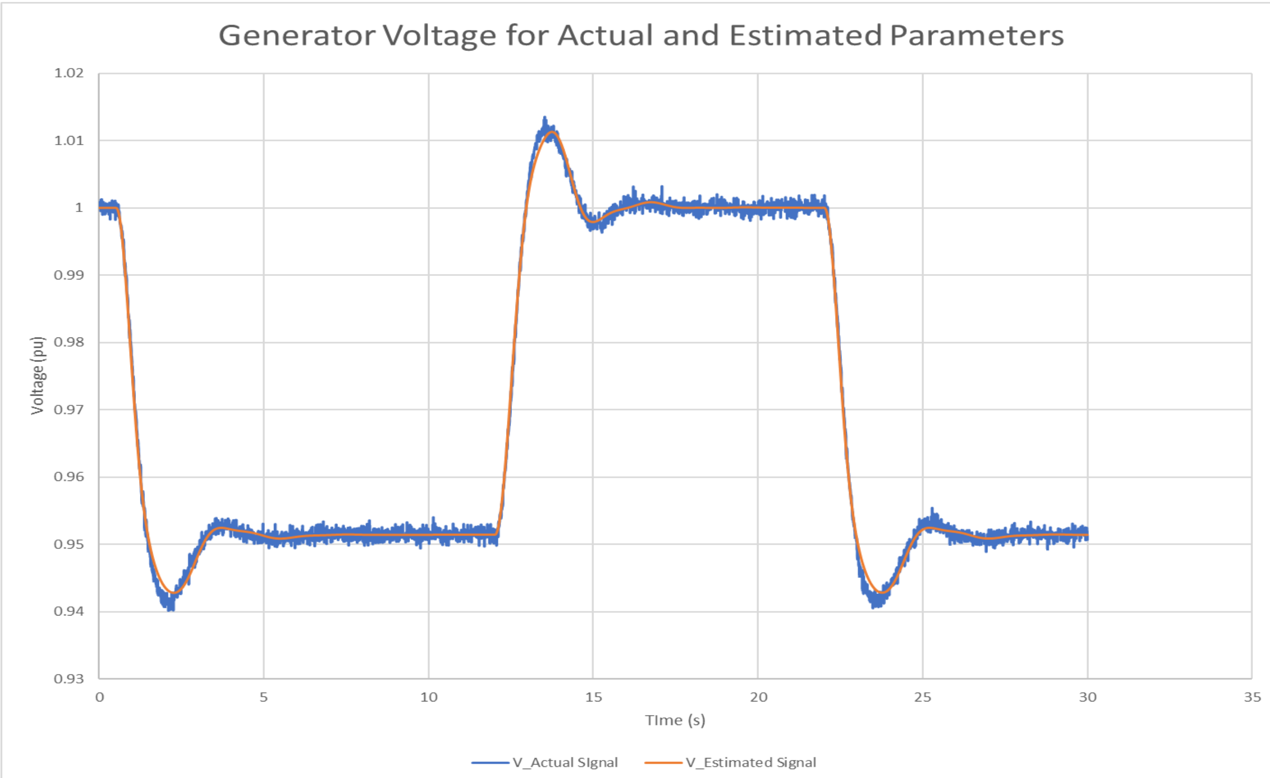

Figure 43: Generator Voltage for Actual and Estimated Parameters

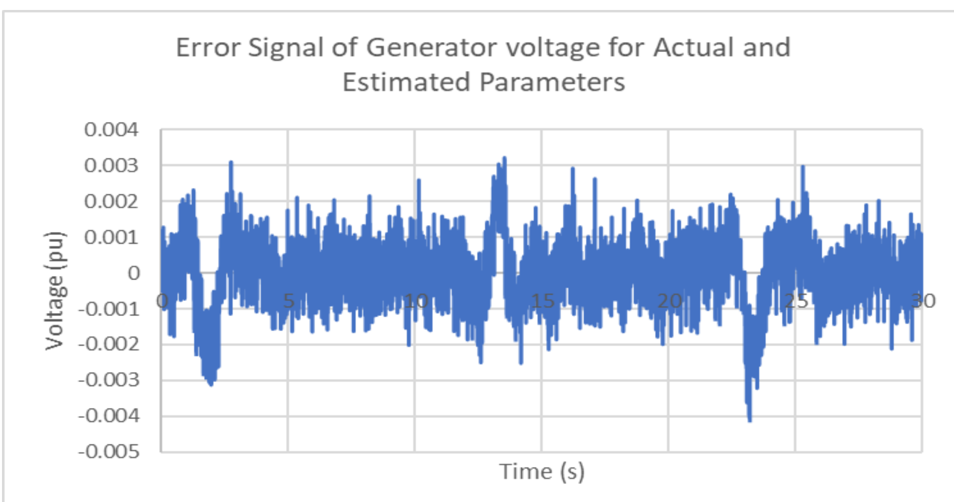

Figure 44: Error Signal for Generator Voltage for Actual and Estimated Parameters

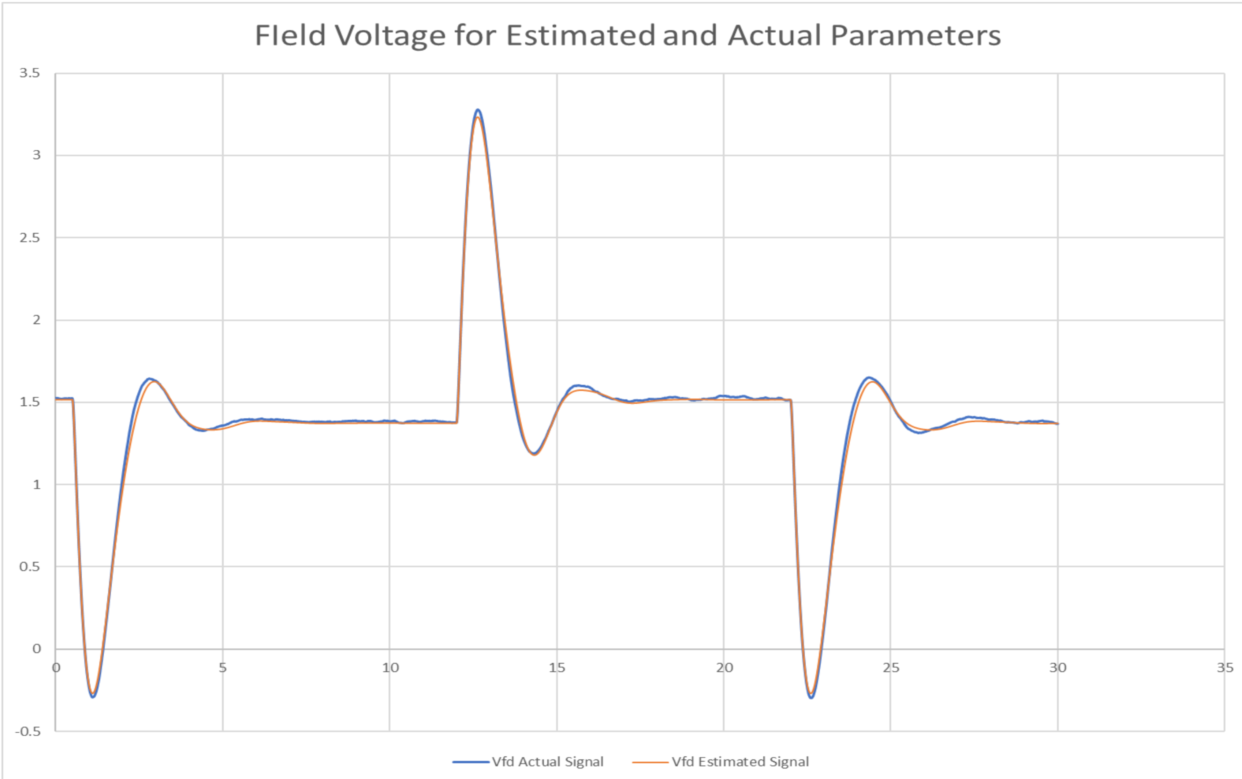

Figure 45: Field Voltage for Actual and Estimated Parameters

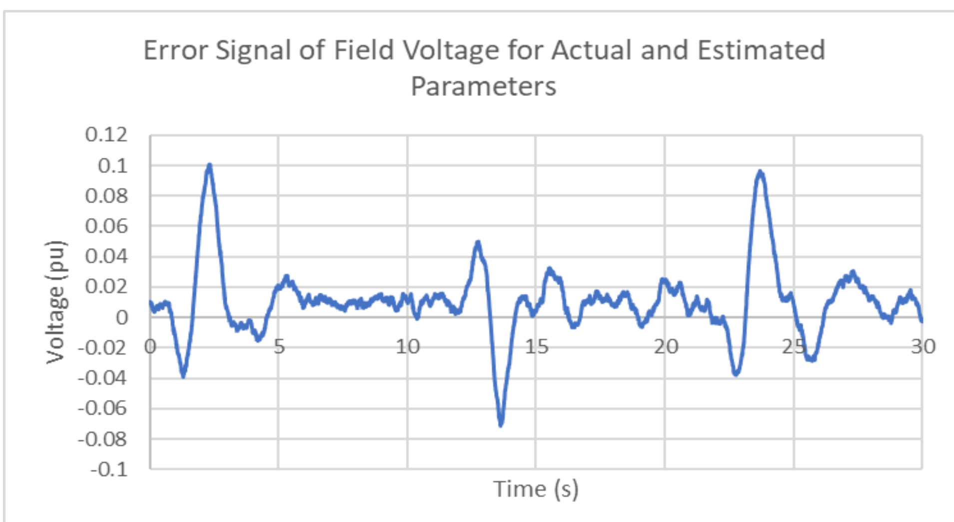

Figure 46: Error of Field Voltage for Actual and Estimated Parameters

According to the results of the simulations with actual generator parameters and estimated parameters, it shows very close behavior. The only difference between these two simulations is the generator parameter values. Hence even there exist around 1% to 4% error of the estimated output compared with the actual values, the behavior of the generator output will have the almost the same. Therefore, it can express that using the estimated results in proposed method in modelling of synchronous generator, it gives very close behavior to the actual behavior.

4.3.1 Validate the Simulation results with the Conventional Standard method results

Following table is extracted from the literature paper on "A guide for Synchronous Generator Parameters. Determination Using Dynamic Simulations Based on IEEE Standards" [2]. This study is based on Standard conventional method of estimating generator parameters using the test method mentioned in section 2.7. Study has conducted in MATLAB SIMULINK environment. The results are as follows,

Parameter	Design value (pu)	Calculated Value (pu)	Difference in Percentage (%)
X_d	1.0495	1.0492	0.03
X'_d	0.3320	0.3293	0.81
X''_d	0.3320	0.3293	8.71
X_q	0.6313	0.6183	2.06
T'_{d0}	3.7724	3.8008	0.75
T''_{d0}	0.0238	0.0245	3.0

Table 6: Final Results of IEEE Standard method [2]

As per the results in Table 6, it is shown that in the conventional test method based on IEEE standard also contains around 1% - 4% difference in average. Here the X''_d has 8.71% value difference. Hence having percentage difference of around 5% for the estimated parameter even in the simulation environment is acceptable.

Hence this proves that the results of the proposed methodology is successful and meaningful in estimating synchronous generator parameters.

4.4 Analysis and Validation of the Test results conducted at Kelanitissa Combined Cycle Power Plant

Summary of the estimation results based on the test data conducted at Kelanitissa Combined Cycle Power Plant as follows,

Parameter	Manufacture's value , pu	Calculated Value, pu	Difference in Percentage (%)
X_d	1.683	1.6343	2.8
X_q	1.452	1.5156	4.3
X_{ad}	1.533	1.4409	6.0
X_f	1.6055	1.5127	5.7
R_f	0.0051	0.004623	9.3
X'_d	0.2193	0.2618	19.3
T'_{d0}	1.008 sec	1.0420 sec	3.3

4.4.1 Validate the results using MATLAB Simulation

To validate the results, estimated values were fed into the MATLAB SIMULINK simulation and obtained the same output signals.

Comparison of the generator terminal voltage. active power and field voltage in the real environment measurement, simulated signals with actual generator parameters and simulated signals with estimated parameters are shown in following figure.

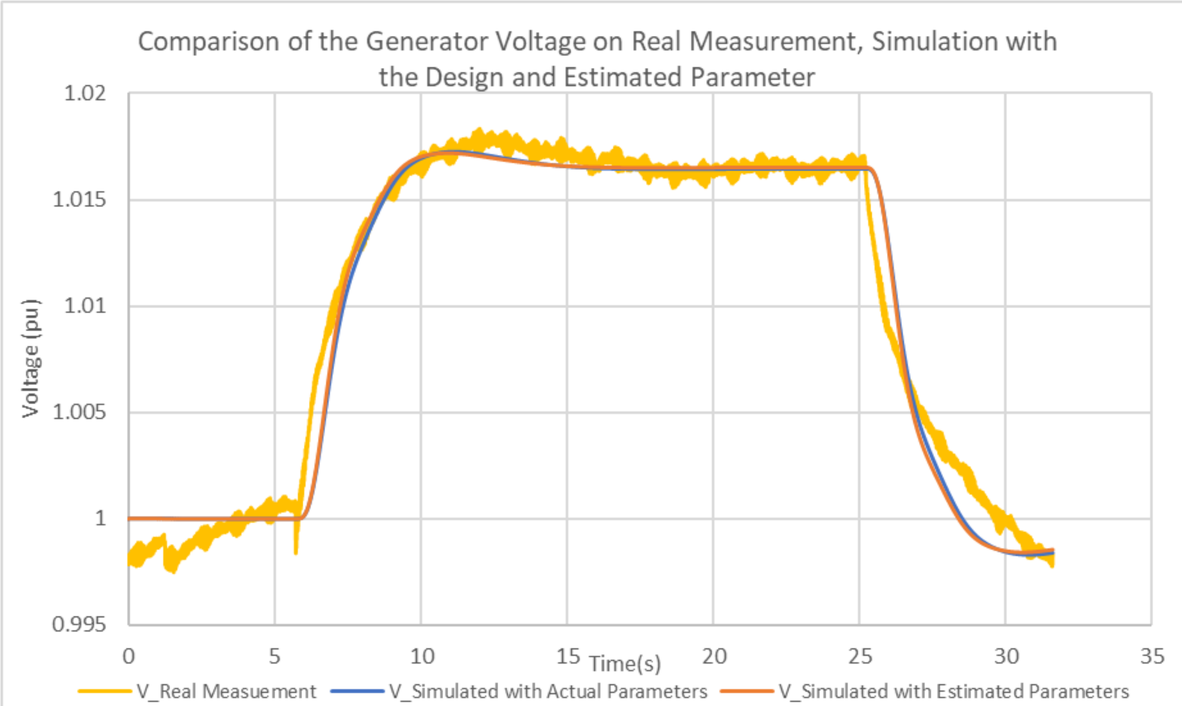

Figure 47: Comparison of Generator Voltage on Real Measurement, Simulation with Actual and Estimated Parameter

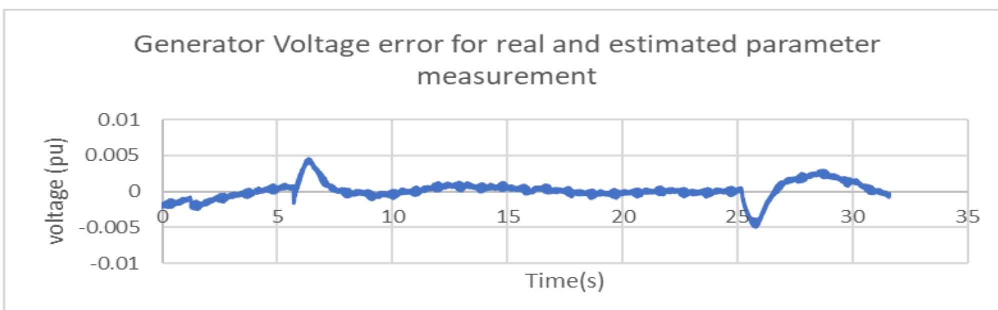

Figure 48: Error Signal of Generator Voltage for real measurement and estimated parameter measurement

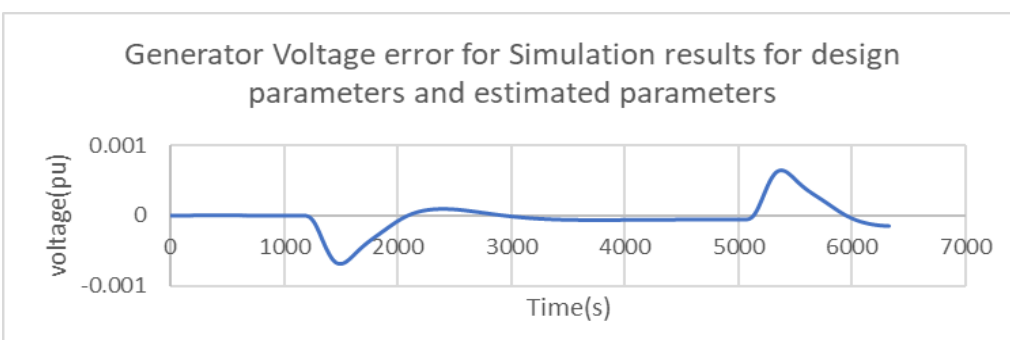

Figure 49: Error Signal of Generator Voltage for Simulation measurement and estimated parameter measurement

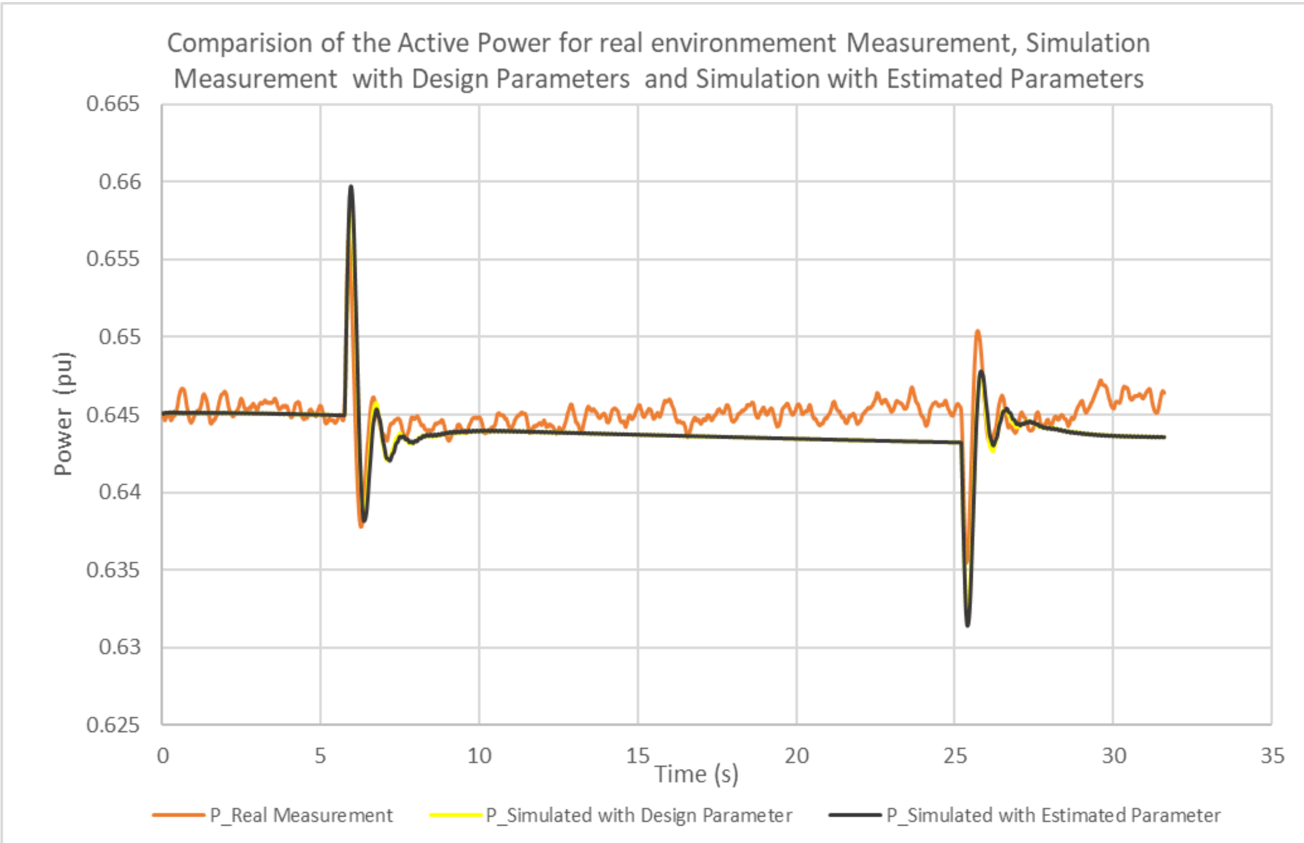

Figure 50: Comparison of the Active Power for real measurement, simulation with Actual and Estimated Parameters

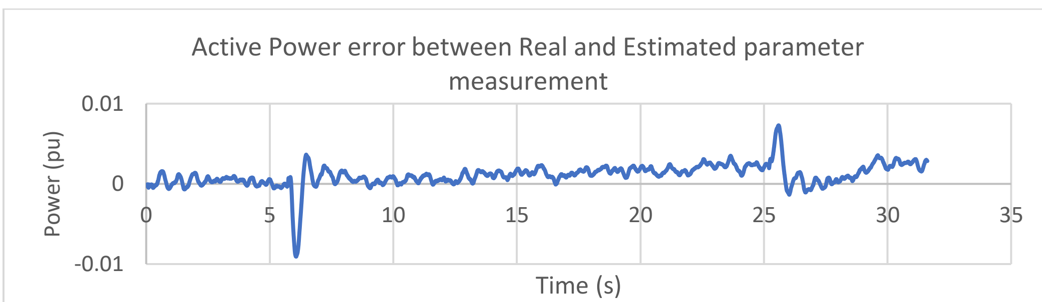

Figure 51: Error Signal of Active Power between real and estimated parameter measurement

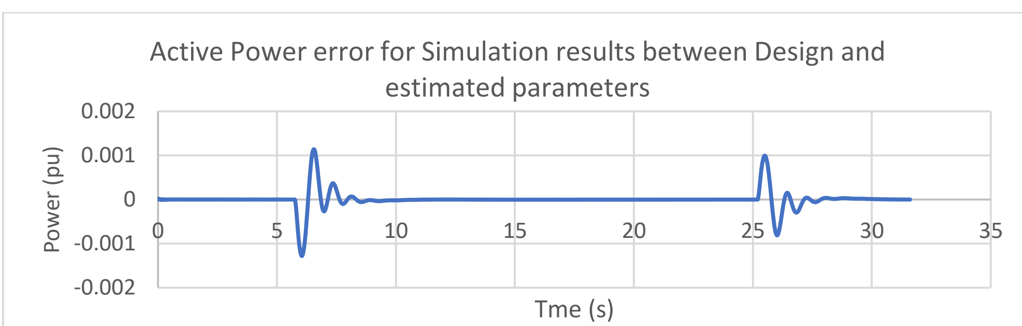

Figure 52: Error Signal of Active Power for simulation results between actual and estimated Parameters

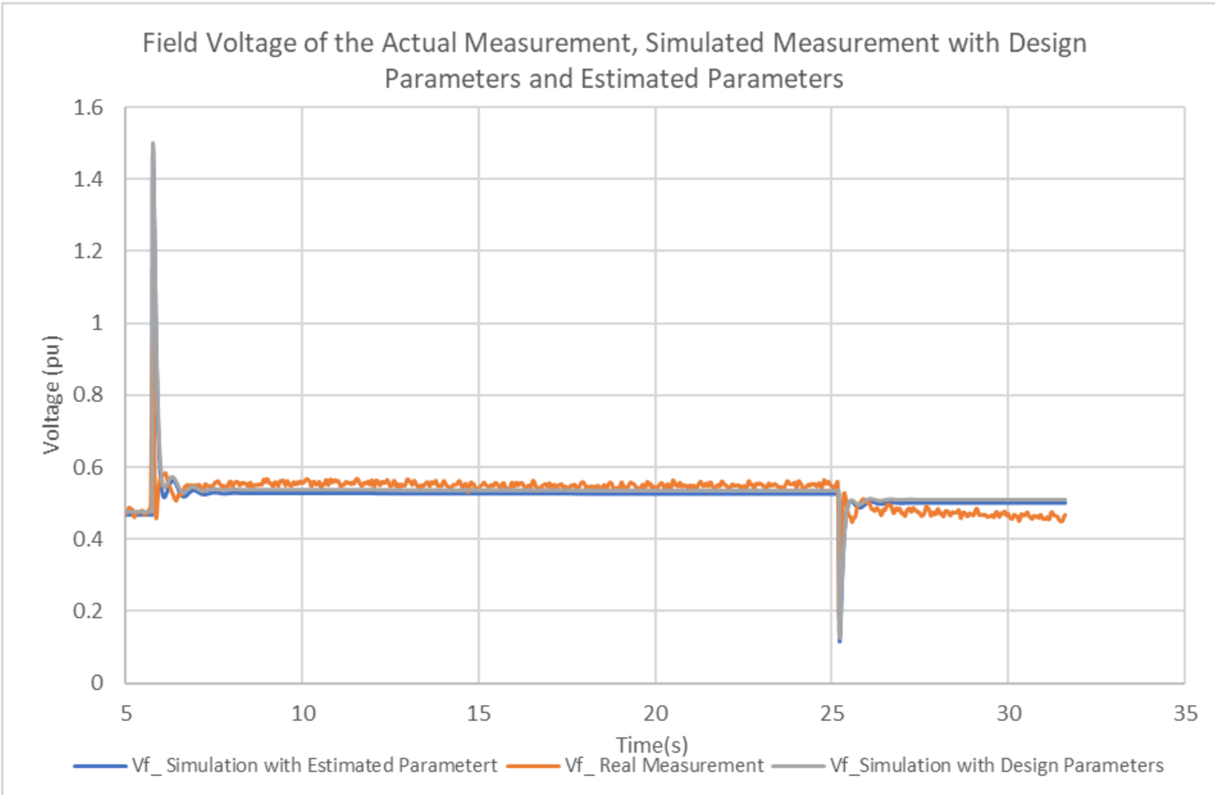

Figure 53: Field Voltage of Actual Measurement, Simulation Measurement with Actual Parameters and estimated parameters

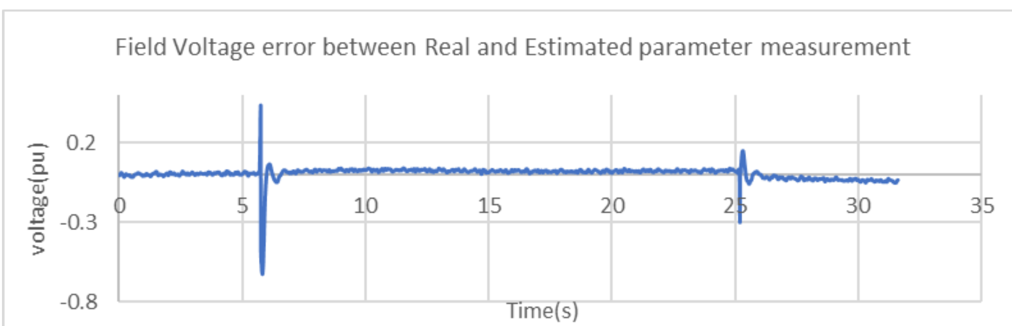

Figure 54: Field Voltage error between Real and estimated parameter measurement

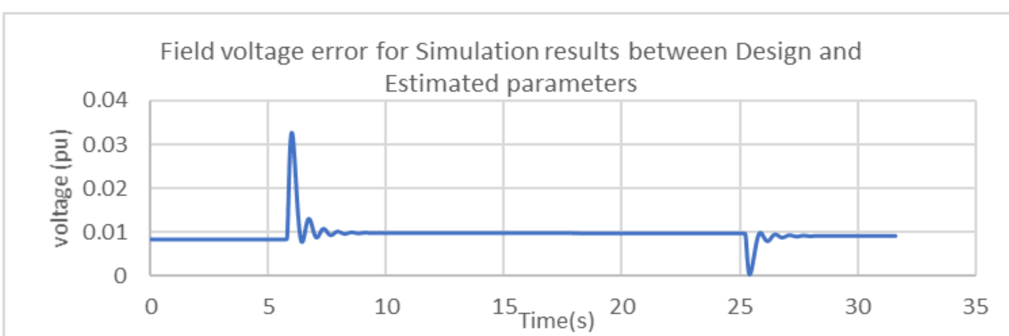

Figure 55: Field Voltage error of Simulation results between actual and estimated Parameters

From the above analysis, it has shown that the MATLAB simulation output results using the estimated parameter have very close behavior to the actual measurement behavior. Maximum error visible between the actual measurement and the estimated measurement are 0.004 pu for generator voltage, 0.0006pu for active power and 0.04pu for field voltage. This is the maximum error which has occurred at the point of the step response is given. Remaining points have very lower error than compared with maximum error. Additionally, simulation has been conducted in two ways. One is considering the design parameters feeding into the synchronous generator block of the Simulink and other one is the estimated parameters feeding into the synchronous generator block. Considering the results of those two shows that the behavior of the active power, Terminal voltage and the field voltage shows almost the same behavior. Therefore, this proves that using the estimated parameter from the proposed methodology in generator modelling shows the same behavior as the actual generator model. Hence this proves that the proposed methodology is successful in estimating generator parameters.

4.4.2 Validate the Experiment results with the IEEE Standard method results

Estimation of Synchronous generator parameter based on IEEE standard test method have conducted in several power plants in Sri Lanka. Here results of two plants are taken for validation. Theory behind this test is discussed in section 2.7

Standard tests were conducted at Victoria Power Plant Unit 2 Generator and New Laxapana Power Plant Unit 2 Generator.

Following tables shows some basic information of the New Laxapana Power Plant Unit 02 Generator and Victoria Power Plant Unit 02 Generator.

Output kVA:	72000 kVA	**Output kW:**	57600 kW
Volts:	12500 V	**Amps:**	3326 A
Power Factor:	0.8	**Frequency:**	50 Hz
Field Volts:	161 V	**Field Amps:**	1538 A
Exciter DC Volts:	112 V	**Exciter DC Amps:**	23.2 A

Table 7: Generator detail on New Laxapana Unit 2

Output kVA:	95000 kVA	**Output kW:**	80750 kW
Speed:	333.3 rpm	**Year:**	1982
Volts:	12500 V	**Amps:**	4388 A
Power Factor:	0.85	**Frequency:**	50 Hz
Field Volts:	220 V	**Field Amps:**	1130 A

Table 8: Generator detail on Victoria Unit 2

After conducting the standard tests on above power plants, results of the estimated parameters and design parameters are listed as follows.

	IEEE Standard Method					
	New Laxapana Power Plant			Victoria Power Plant		
Parameter	Design vale (pu)	Estimated value (pu)	Difference Percentage (%)	Design vale (pu)	Estimated value (pu)	Difference Percentage (%)
X_d	0.900	0.900	0	0.952	0.900	5.4
X_q	0.550	0.566	-3	0.600	0.400	33.33
X_{ad}	0.800	0.783	2.1	0.825	0.773	6.3
T'_{d0}	8.600	3.509	59.19	7.570	8.000	7
X'_d	0.230	0.214	7	0.239	0.315	-31.7

Table 9: Results on Standard Method for New Laxapana and Victoria Power Plant

	Proposed Method					
	Kelanitissa Combined Cycle Power Plant			MATLAB Simulated Machine		
Parameter	Design vale (pu)	Estimated value (pu)	Difference Percentage (%)	Design vale (pu)	Estimated value (pu)	Difference Percentage (%)
X_d	1.683	1.6343	2.8	1.81	1.7814	1.5
X_q	1.452	1.5156	4.3	1.76	1.6928	3.8
X_{ad}	1.533	1.4409	6.0	1.66	1.6314	1.7
T'_{d0}	1.008	1.0420	3.3	8.00	7.937	0.95
X'_d	0.2193	0.2618	19.3	0.3	0.2965	1.18

Table 10: Summary of the Final results in Proposed Method

Based on the results of Standard method results listed in Table 9 and Proposed Method listed in Table 10, following discussion can be made.

1. Considering the IEEE Standard test results, it is observed that there exists a difference in the actual value and the estimated values of very vast range of percentage. Following reasons can be listed for that variation.

    a. Due to the aging of the Generator, the air gap of the stator and rotor can be changed. Victoria Power plant is 25 years old and New Laxpana Plant is 10 years old. Therefore, the air gap can be changed and rotor alignment can be differed from the original position. Once the airgap changes, it'll lead to change the steady and dynamic parameters of the generator.

b. In d axis load rejection, armature current has to be aligned with the d axis and in q axis load rejection test, armature current has to be aligned in the q axis. During real environment testing, it is difficult to maintain the generator voltage, active and reactive power, field current and field voltage at the particular operating point which satisfy the alignment of armature current in d axis or q axis. Additionally, just before the breaker open or load reject, these armature current may differ from the said operating point. This will lead to change the envelop of the voltage measurement, reactive power measurement and the filed current measurement. In the IEEE Standard method, it is required to have the correct envelop of the generator terminal voltage, reactive power and the filed current curves, since the parameters are extracted using those curves.

c. During the IEEE Standard method estimation, in order to obtain parameters for the simulation models, suitable generic models has to be selected from the particular modelling software library to represent the dynamics of the generator. In here, parameters for generator units were estimated to match the field test results by using time domain simulations performed using PSS/E software. Simulation models with the estimated parameters have a dynamic response that closely matches the field test results. Differences remain during the transients when compared with the field test results due to the modeling simplifications.

d. Assumptions are employed in generic models used in simulation studies. These modeling simplifications and assumptions are typical for industry-standard stability programs, such as PSS/E™.

2. Considering the results of the Proposed method in this study which conducted on, Kelanitissa Combined cycle power plant there also exists a difference in the actual value and the estimated values. Following reasons can be listed for that variation.

    a. In the Proposed method, results obtained for Kelanitissa Combined cycle power plant has around 2.5% to 8% value difference. The d axis sub-transient X_d' has 19.3% difference. This plant has built up on year 2001 and now it has been 25 years old and the rotor has been undergone several repairs throughout the period. Hence the airgap of the stator and rotor can be changed. Rotor alignment position can be changed from its original position.

    b. The permittivity of the rotor core material and insulation can be changed due to the aging which will lead to the deviate from the original design parameter values.

c. In the proposed method all the equations have derived considering a 3rd order model. In section 3.1 and 3.2, it has shown that in 3rd order model, effect of the damper winding is neglected, dynamics of the stator winding and Stator resistance is neglected. Due to this reason, equations used for derivation of the major equation becomes simplify with the actual equation. Therefore, the effect of the damper bars and damping winding parameter would not reflect in the derived equation. This will lead to reduce the accuracy of the estimated results.

d. In the MATLAB Simulation model for the proposed method, the exact parameters of the Governor and Exciter is unknown. Hence in the MATLAB Simulink, the governor and exciter models were developed starting with the typical and justifiable values which has the same capacity of the governor and exciters. Then the fine adjustment has been done to obtain the proper behavior of the output signals. Specially at the moment where the step response is given, there will be oscillatory performance in the exciter as well as the governor. So, the behavior during such instants is complex and in order to obtain the accurate functionality, the real existing parameters of the governor and exciter is required. In real practice, during the commissioning these parameters of governor and exciter are tuned in a coordinated manner. If the actual values of the governor and exciter is known then it'll have higher accuracy for the final output estimation.

Therefore, comparing the results of the proposed method with the IEEE Standard method, it shows that the results of proposed method show good justification over the actual values. Hence the parameters estimated by the proposed method can recommended to use in simulation or modelling of the synchronous generator. It is clearly shown that the output of the generator with the estimated parameters shows very close behavior to the actual behavior.

4.5 Limitations

1. This study only covers the transient parameters of the synchronous generator based on the third order model of the synchronous generator. In order to find the sub transient conditions, it is required to select fifth or higher order synchronous generator model.
2. Only the rate of change of field winding flux is considered for the field voltage equation. Therefore, induced flux due to stator current dynamics in the field winding is not considered in this study.

4.6 Suggestions for better validation.

1. Due to the practical issues, IEEE Standard test procedure was not conducted on the same machine which is used to conduct the proposed method. Hence results have been validated using the design data which was given during the commissioning stage which have been conducted 15 to 20 years ago. Hence the existing value might be differed from the design value. Therefore, proper validation can be obtained by conducting the proposed method and IEEE standard test method on the same machine at same time period.

2. For real environment results validation, it is used two power plant test results conducted based on the IEEE standard test procedure. Since these results is available, one can conduct the proposed method in those two machines and validate the results.

3. For MATLAB SIMULINK results validation, two different generators were used. IEEE test methodology results were extracted from the literature paper on "A guide for synchronous generator parameters determination using dynamic simulations based on IEEE standards". It is conducted on 6.25MVA, 4.16kV salient pole generator. Proposed method is conducted on 555MVA, 24kV round rotor generator. Better validation can be obtained by conducting the IEEE standard test procedure on 555MVA, 24kV generator and then compare the results.

Chapter Summary

This chapter describe the results analysis and validation of the proposed method results implemented in MATLAB SIMULINK Simulation environment and real environment experiment conducted at Kelanitissa Combined Cycle Power plant. Further this describes the limitation and suggestions to obtain improved validation. The conclusion of this study will bring out the in the next chapter.

5.0 CONCLUSION

This study is based on the estimation of steady state and dynamic state parameters of synchronous generator while the machine is in running conditions. Synchronous Generator Parameters of X_d, X_q ,X_{ad} , X_f, R_f ,X'_d, $and\ T'_{d0}$ are estimated in this study. In conventional method, the synchronous machine has to take outage from the system and need special preparation. During the test, machine has to undergo several load rejections and sudden short circuit tests. This will lead to stress the machine and endure several disturbances. Therefore, if the machine is old or running under controlled conditions, power plant owners are much reluctant to conduct this kind of tests.

A new methodology has proposed to estimate above mentioned generator parameters by giving 2% - 5% step response to AVR reference point while the machine is connected to the grid. This is not harmful for the machine and can be conducted several times if necessary.

Two newly developed equations are used in this study. In order to develop these equations, 3rd order model is considered where it neglects the effect of damper windings/ damper bars, unbalance conditions, dynamics of stator currents and stator resistance. The derived equations in this study describe the relationship between the generator parameters in d-q-0 domain and time domain. Once the input/output data has been obtained, Nonlinear least square algorithm called gradient based Levenberg Marquardt method which is an iterative method is used to extract the generator parameters.

Proposed method has applied in MATLAB SIMULINK Simulation environment and real environment conducted at Kelanitissa Combined cycle power plant (KCCP), Steam Turbine Generator. From the results of MATLAB SIMULINK Simulation and test conducted at KCCP shows good accuracy compared with the actual values. Proposed method results have validated with the results of Standard tests conducted based on IEEE standards. The results of the proposed method have showed good validation over the actual values and the standard method results. The reasons for the difference between the actual parameter values and the estimated parameter values are discussed in this study.

The simulated outputs using the estimated parameters and the real environment outputs have compared in this study and it has showed that the estimated results have very close behavior to the actual machine behavior. Hence this method can be used to identify the synchronous generator parameter for the older machines which needs to find the existing parameter values or the machines which the parameters of the synchronous generators is completely unknown.

It can conclude that utilizing the results of the proposed methodology can be recommended to use in modelling of the synchronous generators which will give the close behavior of the generator to the actual behavior.

6.0 REFERENCE

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7.0 ANNEXES

Matlab Code for NLS- Levenberg Algorithm

```
datap=6300;
ita=0.01;
alpha=100;
n=600;

for k=1:1:n
for i=1:1:datap
 e1(i,1)=[P(i,1)-P_sim(i,1)];
 e2(i,1)=[Vt(i,1)-Vt_sim(i,1)];
end

e=[e1;e2];
I=e.'*e;
theta(:,1,1)=[1.5;1.5;1.3];
JJ1= [-(cos(delta(1,1))*sin(delta(1,1))*(P(1,1)^2 - Q(1,1)^2)-
(P(1,1)*Q(1,1)*(2*sin(delta(1,1))^2 -
1)))/Vt(1,1)^2,(cos(delta(1,1))*sin(delta(1,1))*(P(1,1)^2 - Q(1,1)^2)
-(P(1,1)*Q(1,1)*(2*sin(delta(1,1))^2 - 1)))/Vt(1,1)^2,
(Ifd(1,1)*(P(1,1)*cos(delta(1,1)) - Q(1,1)*sin(delta(1,1))))/Vt(1,1)];

JJ2= [((2*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(3,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))/(2*(Ifd(1,1)^2*theta(3,:,1)^2 +
(theta(1,:,1)^2*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 +
(theta(2,:,1)^2*(P(1,1)*cos(delta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(3,:,1)*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))^(1/2)),(theta(2,:,1)*(P(1,1)*cos(del
ta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/(Vt(1,1)^2*(Ifd(1,1)^2*theta(3,:,1)^2 +
(theta(1,:,1)^2*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 +
(theta(2,:,1)^2*(P(1,1)*cos(delta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(3,:,1)*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))^(1/2)),(2*theta(3,:,1)*Ifd(1,1)^2 -
(2*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))*Ifd(1,1))/Vt(1,1))/(2*(Ifd(1,1)^2*theta(3,:,1)
^2 + (theta(1,:,1)^2*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 +
(theta(2,:,1)^2*(P(1,1)*cos(delta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(3,:,1)*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))^(1/2))];
```

```
for i=1:1:datap
J1(:,:,i)= [-(cos(delta(i,1))*sin(delta(i,1))*(P(i,1)^2 - Q(i,1)^2)-
(P(i,1)*Q(i,1)*(2*sin(delta(i,1))^2 -
1)))/Vt(i,1)^2,(cos(delta(i,1))*sin(delta(i,1))*(P(i,1)^2 - Q(i,1)^2)
-(P(i,1)*Q(i,1)*(2*sin(delta(i,1))^2 - 1)))/Vt(i,1)^2,
(Ifd(i,1)*(P(i,1)*cos(delta(i,1)) - Q(i,1)*sin(delta(i,1))))/Vt(i,1)];
end

for i=1:1:datap
J2(:,:,i)= [((2*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(3,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))/(2*(Ifd(i,1)^2*theta(3,:,k)^2 +
(theta(1,:,k)^2*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 +
(theta(2,:,k)^2*(P(i,1)*cos(delta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(3,:,k)*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))^(1/2)),(theta(2,:,k)*(P(i,1)*cos(del
ta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/(Vt(i,1)^2*(Ifd(i,1)^2*theta(3,:,k)^2 +
(theta(1,:,k)^2*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 +
(theta(2,:,k)^2*(P(i,1)*cos(delta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(3,:,k)*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))^(1/2)),(2*theta(3,:,k)*Ifd(i,1)^2 -
(2*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))*Ifd(i,1))/Vt(i,1))/(2*(Ifd(i,1)^2*theta(3,:,k)
^2 + (theta(1,:,k)^2*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 +
(theta(2,:,k)^2*(P(i,1)*cos(delta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(3,:,k)*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))^(1/2))];
end

for i=1:1:datap-1
 JJ1=[JJ1;J1(1,:,i+1)];
end

 for i=1:1:datap-1
 JJ2=[JJ2;J2(1,:,i+1)];
 end

  Jac = [JJ1;JJ2];

  theta(:,1,k+1)=theta(:,1,k)-ita*(inv(Jac'*Jac+alpha*I))*Jac'*e;
alpha = alpha-0.01;
end

for i= 1:1:n
```

```
Xd(i,:)=theta(1,:,i);
Xq(i,:)=theta(2,:,i);
Xad(i,:)=theta(3,:,i);
end


datap=6300;
ita=0.1;
alpha=100;
n=600;
Xad = 1.4409;

for k=1:1:n
for i=1:1:datap
 e1(i,1)=[Vfd(i,1)-Vfd_sim(i,1)];
% e2(i,1)=[Vt(i,1)-Vt_sim(i,1)];
end

e=[e1];
I=e.'*e;
theta(:,1,1)=[0.348;1.5];
JJ1= [Ifd(1,1),IfdD(1,1)];
%JJ2= [((2*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(2,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))/(2*(Ifd(1,1)^2*theta(2,:,1)^2 +
(theta(1,:,1)^2*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 +
(theta(2,:,1)^2*(P(1,1)*cos(delta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(2,:,1)*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))^(1/2)),(theta(2,:,1)*(P(1,1)*cos(del
ta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/(Vt(1,1)^2*(Ifd(1,1)^2*theta(2,:,1)^2 +
(theta(1,:,1)^2*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 +
(theta(2,:,1)^2*(P(1,1)*cos(delta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(2,:,1)*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))^(1/2)),(2*theta(2,:,1)*Ifd(1,1)^2 -
(2*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))*Ifd(1,1))/Vt(1,1))/(2*(Ifd(1,1)^2*theta(2,:,1)
^2 + (theta(1,:,1)^2*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 +
(theta(2,:,1)^2*(P(1,1)*cos(delta(1,1)) -
Q(1,1)*sin(delta(1,1)))^2)/Vt(1,1)^2 -
(2*Ifd(1,1)*theta(2,:,1)*theta(1,:,1)*(Q(1,1)*cos(delta(1,1)) +
P(1,1)*sin(delta(1,1))))/Vt(1,1))^(1/2))];
for i=1:1:datap
J1(:,:,i)= [Ifd(i,1),IfdD(i,1)];
end
```

```
%for i=1:1:datap
%J2(:,:,i)= [((2*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(2,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))/(2*(Ifd(i,1)^2*theta(2,:,k)^2 +
(theta(1,:,k)^2*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 +
(theta(2,:,k)^2*(P(i,1)*cos(delta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(2,:,k)*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))^(1/2)),(theta(2,:,k)*(P(i,1)*cos(del
ta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/(Vt(i,1)^2*(Ifd(i,1)^2*theta(2,:,k)^2 +
(theta(1,:,k)^2*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 +
(theta(2,:,k)^2*(P(i,1)*cos(delta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(2,:,k)*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))^(1/2)),(2*theta(2,:,k)*Ifd(i,1)^2 -
(2*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))*Ifd(i,1))/Vt(i,1))/(2*(Ifd(i,1)^2*theta(2,:,k)
^2 + (theta(1,:,k)^2*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 +
(theta(2,:,k)^2*(P(i,1)*cos(delta(i,1)) -
Q(i,1)*sin(delta(i,1)))^2)/Vt(i,1)^2 -
(2*Ifd(i,1)*theta(2,:,k)*theta(1,:,k)*(Q(i,1)*cos(delta(i,1)) +
P(i,1)*sin(delta(i,1))))/Vt(i,1))^(1/2))];
%end

for i=1:1:datap-1
 JJ1=[JJ1;J1(1,:,i+1)];
end

 %for i=1:1:datap-1
 %JJ2=[JJ2;J2(1,:,i+1)];
 %end

  Jac = [JJ1];

  theta(:,1,k+1)=theta(:,1,k)-ita*(inv(Jac'*Jac+alpha*I))*Jac'*e;
end

for i= 1:1:n
Rf(i,:)=theta(1,:,i);
Xf(i,:)=theta(2,:,i);
%Xad(i,:)=theta(3,:,i);
end
```