KALMAN FILTER BASED IMPEDANCE PARAMETER ESTIMATION FOR TRANSMISSION LINE AND DISTRIBUTION LINE

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ABSTRAK

Pengetahuan yang secukupnya tentang ketepatan nilai parameter impedans dalam penghantaran arus elektrik boleh membantu meningkatkan prestasi sesebuah sistem. Pada masa kini, terdapat pelbagai kaedah yang digunakan untuk mengenalpasti nilai parameter impedans di dalam sesebuah sistem tetapi kaedah tersebut adalah terhad disebabkan oleh teknologi dan kewangan yang tidak mencukupi. Yang paling utama, kebanyakan algoritma yang digunakan adalah berasaskan andaian bahawa semua penghantaran elektrik dihantar sepenuhnya dan komponen yang terlibat adalah simetrik. Walau bagaimanapun, keadaan ini adalah tidak benar untuk sistem tertentu atau sistem yang melibatkan voltan rendah. Dalam kes seperti ini, untuk penghantaran yang tidak dipindahkan sepenuhnya, tiga rangkaian akan digabungkaan. Kaedah pengukuran positif akan di gunakan sekaligus menghasilkan bacaan parameter yang tidak tepat. Oleh itu, satu kajian terperinci tentang pembinaan dan penilaian algoritma baru untuk anggaran parameter impedans dalam penghantaran arus elektrik telah diambil kira di dalam tesis ini. Anggaran tentang parameter impedans dalam penghantaran arus elektrik telah menjadi realiti dengan adanya kaedah pengiraan dan jangkaan menggunakan komputer. Oleh itu, kajian ini menunjukkan pembinaan penapis Kalman menggunakan MATLAB simulink untuk menganggarkan nilai parameter RXB dan RLC yang tepat dalam penghantaran dan pengedaran arus elektrik. Penyelidikan ini juga melaporkan prestasi kaedah penapis Kalman dalam penghantaran elektrik berbanding dengan kaedah lain seperti kaedah *Linear Least Square* dan kaedah *Synchornous Phasor Measurement*. Untuk menunjukkan kecekapan cadangan kaedah baru ini, pengiraan parameter impedans dalam penghantaran arus elektrik telah dilaksanakan dan satu kajian kes di UMP juga telah diambil kira. Pertama, data yang diterima dari kawasan penyelidikan seperti voltan, arus, faktor kuasa dan reka bentuk penapis Kalman dibentangkan. Pemodelan penapis Kalman dinilai menggunakan MATLAB untuk memastikan tidak ada masalah teknikal dengan penapis Kalman itu sendiri. Kemudian nilai set data seperti voltan, arus dan faktor kuasa yang diperoleh digunakan untuk menganggarkan nilai baru parameter RXB dan RLC. Keputusan menunjukkan bahawa ketepatan yang lebih tinggi dengan 98.64% dalam anggaran nilai parameter RXB dan RLC yang lebih baik daripada yang diperolehi. Dengan ini dapat disimpulkan bahawa penapis Kalman boleh digunakan untuk menganggarkan sesuatu nilai dengan lebih tepat khususnya untuk paramater RXB dan RLC.

ABSTRACT

Accurate knowledge of impedance parameters in transmission line can helps to improve the performance of a system. Currently, methods for parameter identification in transmission line are various but limited due to the insufficient technology and finance. Most of the current algorithms for parameter identification are based on the assumption that transmission line is fully transposed and the corresponding components are symmetric. However, this is not true for certain low voltage systems or systems with short lines. In these cases, for transmission lines that are not fully transposed, the three sequence networks will be mutually coupled. The positive sequence measurement is use to estimate the positive sequence parameters which will generate inaccurate parameter estimates. Therefore, a detailed study on developing and evaluating the new algorithms for transmission line parameter estimation is considered in this thesis. The estimation of impedance parameters in transmission line has become possible with the availability of computational and prediction method. Therefore, this research presents the development of Kalman Filter model by using MATLAB simulink in order to estimate the accurate values of RXB and RLC parameters in transmission line. This research also reports the performance of Kalman Filter method in transmission line compared with the other methods such as *Linear Least Square* method and *Synchronous Phasor Measurement* method. To demonstrate the efficiency of the new proposed method, a case study of simulated distribution line in UMP is also considered. Firstly, the data set from the research areas such as voltage, current, power factor and design of Kalman Filter are presented. The modeling of Kalman Filter was evaluated by using MATLAB simulink to ensure there is no technical problem with the Kalman Filter itself. Then, the data set values such as voltage, current and power factor are used to estimates the new values of RXB and RLC parameters. The results showed that the higher accuracy with 98.64% in the estimation of RXB and RLC parameter values which are better than what was obtained. From this, it is shown that Kalman Filter is possible to use in the estimation areas especially for RXB and RLC parameters.

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LIST OF SYMBOLS

R	Resistance
X	Reactance
S	Susceptance
L	Inductance
C	Capacitance
Ω	Ohm
H	Henry
F	Farad
Hz	Frequency
V	Voltage
A	Ampere

LIST OF ABBREVIATIONS

UMP	Universiti Malaysia Pahang
KF	Kalman Filter
LLS	Linear Least Square
PMU	Synchronous Phasor Measurement
OLS	Ordinary Least Squares
WLS	Weighted Least Squares
EMI	Electromagnetic Interference
RFI	Radio Frequency Interference
AC	Alternate Current
DC	Direct Current

CHAPTER 1

INTRODUCTION

1.1 Chapter overview

This chapter covers the introduction for estimation of parameter values in long transmission line by using Kalman Filter method. In the introduction section, several facts and figures regarding the estimation of parameter values in the system will be discussed. Problem statement, objectives, contribution, scope of project, and thesis outline are also presented in this chapter.

1.2 Introduction

Electricity is transmitted from electric power station to supply various industries and household applications everyday. It is a need for making the human life better by delivering sufficient power and energy for numerous purposes. Figure 1.1 shows the prototype of topology and features of today's transmission lines. Transmission line receives "stepped up" electric power by trasformer of numbers of thousands volts at generating plant (Harrison, 1982). Distribution lines of different load center obtained lower voltage as the transformer step down the power at some substations in the transmission system (Ravish R. Singh, 2003) (Mishra & Centeno, 2015). Variable outputs of the sources can cause unplanned dynamics, so the transmission capacity of the power system have to be sufficiently enough to handle the situation. The system must also stable without creating any overcrowding from renewble sources to load centers. As a result then the generated energy can be transported in long distances(Ren, Member, & Levari, 2018). According to U.S. - Canada Power System Outage Task Force, the transmission and distribution of electricity from the power plant or generators to the end user is the aggregate interconnection of lines of networks which delivers specific voltage. It is about 230 V to an ordinary or residential consumers and an intermediate around 12,000 V or more to industries or companies (U.S.-Canada Power System Outage Task Force, 2004).

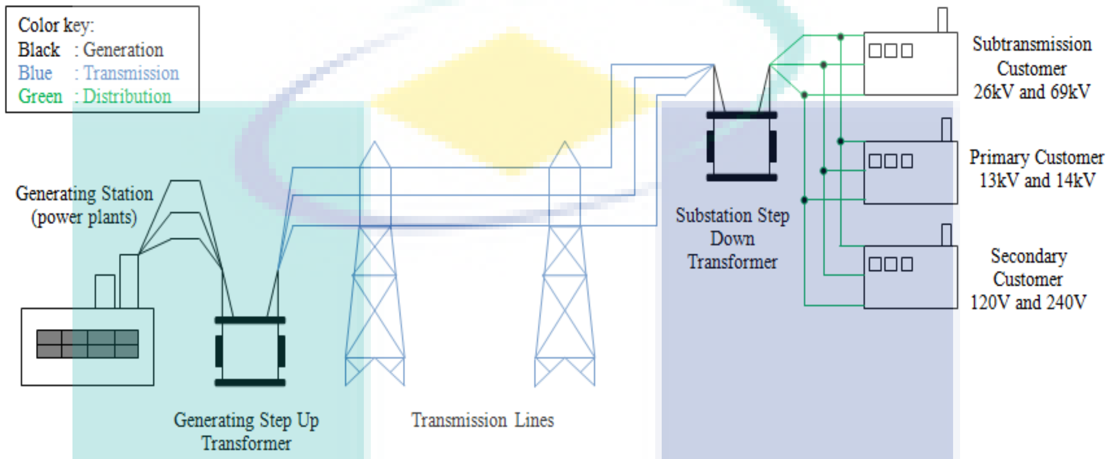

Figure 1.1 Power distribution system

All transmission lines in a power system exhibit the electrical properties of resistance, reactance and susceptance (Illias, Halim, Bakar, Mokhlis, & Halim, 2012). In designing and operating transmission line the purpose of voltage drop, line losses and efficiency of transmission line need to be considered significantly (Shi, Tylavsky, Koellner, Logic, & Wheeler). These values are greatly influenced by these three parameters which are resistance (R), reactance (X) and susceptance (B) (Poornima & Sharma, 2014). Power system state estimation is a main tool of energy management system. Schweppe and Wildes are the first whose to apply state estimation in power systems in the late 1960s (Saikia & Mehta, 2016)(Alazard, 2011). Several applications and techniques of Kalman Filter have been one of the famous methods in power system estimation ever since. It has been used for damping and frequency (Larsson & Rehtanz, 2003), modal changes (Wiltshire, Ledwich, Member, & Shea, 2007), state estimation (Vadirajacharya & Lonere, 2015), and power factor detection. However, these researches did not emphasize the important indicators that give great effects in the system which are R, X and B parameters. IEEE systems are being focused mainly by most of these papers but lacking of evaluation on real system. One of the systems that have been tested is for long transmission line in 2015 by Costa et al.(Costa & Kurokawa, 2015). Theoretically, in short transmission line the values of R, X and B are lower than long transmission line. But due to some circumstances, the values of R, X and B are directly related to its physical properties such as type of cable, size of cable, length of cable and number of winding which are tightly depends on its tolerances. These situations can be categorized as noises in the estimation system.

Noise is generally an unwanted disturbance occurred in the electrical signal. Noise can be constant or random and can be temporarily available. Constant noise can be due to the predictable 50 or 60 Hz AC 'hum' from power circuits or harmonic multiples of power frequency which is closed to the data communications cable (Shi, Tylavsky, Logic, & Koellner, 2008). On the other hand, unpredictable transient noise is caused, for example, by lightning. Noise can also be generated from within the system itself (internal) or from an outside source (external). Thermal noise and imperfections are the example for internal noise, while natural origins, electromagnetic interference (EMI), radio frequency interference (RFI) and cross talk are the examples of external noise in the system. All of these properties can directly influence the values of R, X and B in the transmission line.

The presence of noise and system dynamics is the conditions that made the difference between real situation and theoretical analysis. This can be the perspective to be observed in order to understand the behaviour of the system the practical analysis (Shi et al., 2008) (Mishra & Centeno, 2015). Power losses, fault, and voltage drop can be obtained for analysis purpose from real system (Kumar & Dhiraj, 2012). Therefore, this will create an opportunity for researcher to provide a suitable corrective action according to the circumstances. As a result, the determination for the future condition in transmission line can be identified. The load applied in the system can accurately determine the type, size and length of the cable as the theoretical analysis and the real system shows the similar result.

The accuracy of power flow modelling, fault location and transient stability influenced by the accuracy of transmission line parameters understanding (Sameepa & Don, 2016) . Previously, calculations based in conductor dimensions, sag and line length were used to estimate these parameters (Alrawashdeh, 2014). However, due to the assumptions and approximation involved, the estimation was not reliable for real -

time application (Shi et al., 2008). Therefore, this issue has inspired this research to examine the R (resistance), X (reactance) and B (susceptance) parameter values for transmission line. The analysis focusing on a transmission line for a substation located in Midland, England. This substation was chosen because of the required data is available and has been evaluated by a number of approaches (Ritzmann, Wright, Holderbaum, & Potter, 2016). Other than that, this data also has been used to estimate the R, X and B parameters by using other estimation method which are Linear *Least Square* method and *Synchronous Phasor Measurement* method. Hence, the comparison between Kalman Filter method and those two techniques examining the system accuracy.

For further clarification purposes, a simulation on UMP distribution line also has been carried out as a case study to prove that Kalman Filter method is one of the most suitable methods for estimation. It is also worth to mention that, currently UMP does not have any information about the parameters of the transmission line. This situation has produced difficulties to reduce the operating cost and maintenance operations. To overcome this issue, Kalman Filter method is used for estimation of R (resistance), L (inductance) and C (capacitance) values for distribution line in UMP. The analysis mainly investigates the R, L, and C parameters. Mathematical model for UMP transmission line is designed by using standard parameters. This analysis attempts to provide information for Department of Property Management and Development in UMP about the transmission line to understand the system performance as well as to execute a corrective action accordingly based on the given results.

In this research, a model in MATLAB simulink is developed to analyze the substation in Midland, England transmission line and Universiti Malaysia Pahang (UMP) distribution line by considering different noise characteristics to reprint certain unknown parameters which are difficult to predict. Kalman Filter algorithm is used to minimize the noise error in the system in order to get the accurate estimation of RXB and RLC values. The data is then used for comparison purposes between the calculated and estimated values with other method. Since the parameters of RXB and RLC are used in most of the system, the importance of RXB and RLC in transmission line needs to be studied. Thus, this study will provide an overview of the characteristics RXB and

RLC in an equivalent circuit and the effects of RXB and RLC in circuit are also taken into consideration.

This thesis is started with discussion of the introductory part of the study followed by the literature review to relate previous researches conducted around the area of the study. The third chapter is discussing the method used during the whole project. The result and analysis is discussed in chapter four to explain all analysis of the project. The last part of the report will include the conclusion of the study and the reference along with the appendix.

1.3 Problem statement

Power transfer in transmission line has become a critical issue due to the RXB and RLC parameters. Based on the previous research by G. Chen, it was stated that the method of analysing R, L and C parameter values in a circuit is never constant (Chen & Friedman, 2006). Since the RXB and RLC parameters are appeared in every system, a proper understanding of the system is necessary in order to know what happen to the system when any of the RXB and RLC parameter is altered. A number of approaches have been proposed to reduce the impact of random errors in *Least Square* method and *Synchronous Phasor Measurement* method on impedance parameter determination such as unbiased linear least squares (LS) estimation and non-linear LS algorithm. However, it should be noted that there is no specific research done to prove that the RXB and RLC parameters estimation in real power system by using Kalman Filter method. Kalman Filter algorithm is used to minimize the noise error in the system in order to get the accurate estimation of RXB and RLC values. Therefore, it is the main intention of this project to justify the RXB and RLC parameters and the system performance according to the circumstances mentioned above. Estimation of R, L and C parameters for UMP distribution line is used as case study to prove the reliability of Kalman Filter in the system.

1.4 Objectives

The objectives of this research are:

i. To develop Kalman Filter based estimation for RXB and RLC parameter for transmission line in Midland, England and distribution line in Universiti Malaysia Pahang.

ii. To compare and analyse the performance of Kalman Filter method in transmission line with Linear *Least Square* method and *Synchronous Phasor Measurement* method.

1.5 Scope of research

The aim of this research is to estimate parameter values in single phase transmission line located in substation in Midland, England and UMP distribution line as a case study to evaluate Kalman Filter performances. In this case, the flow of the operation starts with the design of equivalent circuit by using MATLAB simulink. In developing the equivalent circuit, it is important to take note of the parameters involved in transmission line. Kalman Filter is used to estimate the parameter values in transmission line in order to reducing the unknown errors in the system. Comparison between Kalman Filter method with Linear *Least Square* and *Synchronous Phasor Measurement* method also taken into consideration. As a case study, UMP distribution line is used to prove that Kalman Filter method is the most suitable method for parameters estimation. Last but not least, the research is assumed to prove that the parameters influence the performance of transmission line. The comparison between calculated and estimated values of RXB and RLC are also taken into consideration.

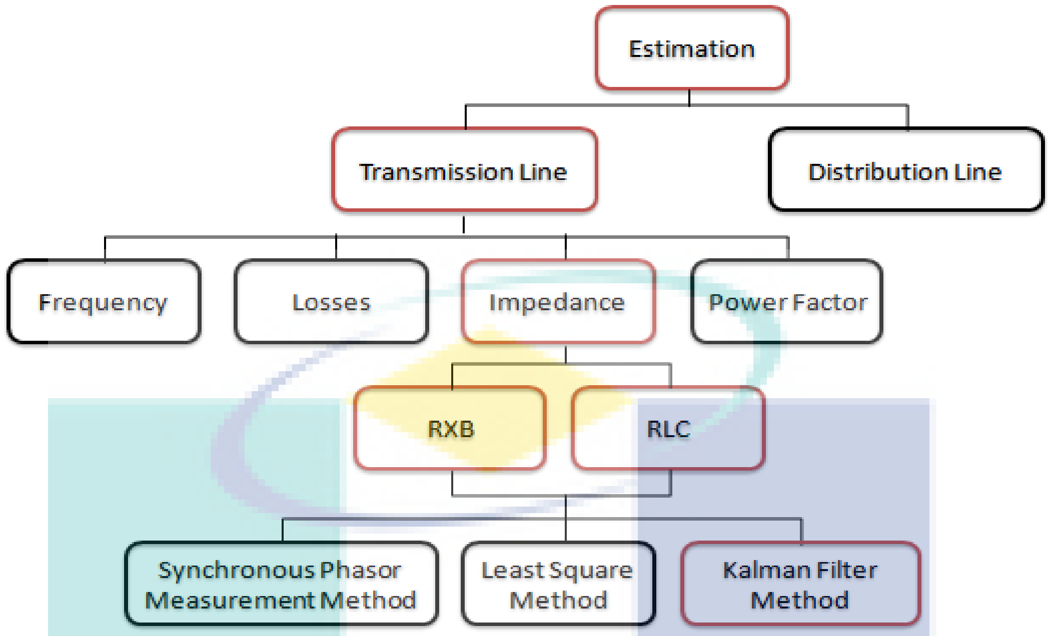

Figure 1.2 Overall scope of this research

1.6 Contribution

The main contribution of this research to the country is to provide more accurate estimation technology through prior estimation and prediction of the whole system by using Kalman Filter technique. As the current technology does not apply this function, it will be a wise decision to design a new technique that will be able to predict the output which can save a lot of time for designing purposes.

1.7 Thesis outline

This thesis consists of five chapters which explain about the estimation of RXB and RLC parameter for transmission line. The content of each chapter will be discussed as follows:

Chapter 1 discussed the background of the project such as estimation of RXB and RLC parameter and development the Kalman Filter by using Maltab simulink software. It also includes the objectives, problem statement and scope of work.

Chapter 2 covers the literature review, discuss about the previous research done by other researchers in the same area and relevant issues along with some comparison with the previous research. The comparison of performance accuracy also has been made between Linear *Least Square* method and *Synchronous Phasor Measurement* method in transmission line.

Chapter 3 discusses about the methodology of the project to achieve the objectives stated in this project. This methodology shows the flow process of the experimental research and firstly focussed to the development of the system such as modelling of Kalman Filter simulink by using MATLAB Software. The simulation that have been planned are stated in the scope of work section

Chapter 4 presents about the evaluation performance of the developed system and techniques to develop Kalman Filter based estimation for RXB and RLC parameter for transmission line. In this part, the performance of Kalman Filter method in transmission line with Linear *Least Square* method and *Synchronous Phasor Measurement* method will be discussed. The data collected from the simulation will be presented and discussed.

Chapter 5 provides conclusion of the estimation for RXB and RLC parameter for transmission line and a full conclusion for the whole research. Summary of the work is listed and the contribution of this project is highlighted as well as the recommendations for the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Chapter overview

In this chapter, the basic knowledge related to estimation of parameters in transmission line is described. An overview for Kalman Filter is discussed further along with its characteristic. Lastly, the design of equivalent circuit is mentioned by stating its standard parameters.

2.2 Introduction

Transmission line is defined as the path of carrying alternating electrical energy from source to load (Hill, 2004). It has three constant of resistance, R, reactance, X and susceptance, B which distributed along the whole length of the line (Ritzmann, Wright, Holderbaum, & Potter, 2016). Transmission line can be classified into three categories; short, medium and long transmission line (Oke & Bamigbola, 2013).

The length for short transmission line is up to about 50 km and the voltage is comparatively lower than 20 kV. Due to smaller length and lower voltage, the capacitance effect is small and can be neglected (Javed, Aftab, Qasim, & Sattar, 2008). Therefore, only resistance and inductance will be considered. The equivalent circuit of short transmission line is shown as Figure 2.1.

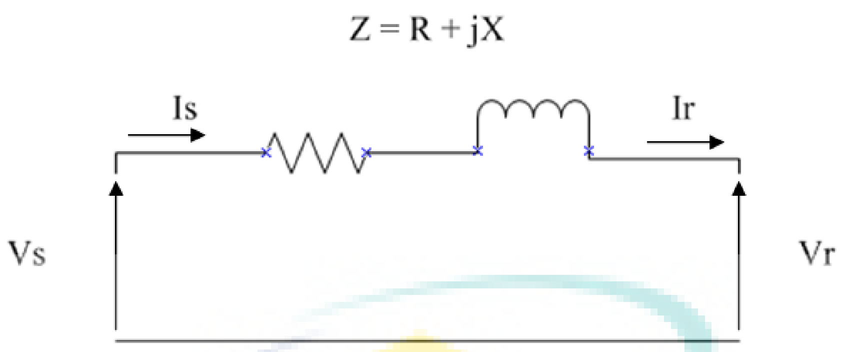

Figure 2.1 Short transmission line

The length for medium transmission line is up to about 50 - 150 km and the voltage is moderately high between 20 – 100 kV. Due to sufficient length and lower voltage, the capacitance effect is considered and cannot be neglected. Therefore, resistance, inductance and capacitance will be considered. The equivalent circuit of medium transmission line is shown as Figure 2.2.

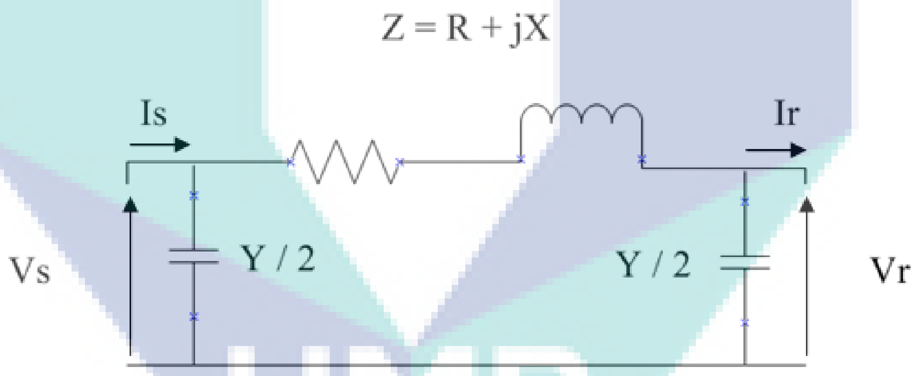

Figure 2.2 Medium transmission line

The length for long transmission line is more than 150 km and the voltage is higher than 100 kV. The line constant are considered uniformly distributed aver the whole length of the line. The equivalent circuit of long transmission line is shown as Figure 2.3.

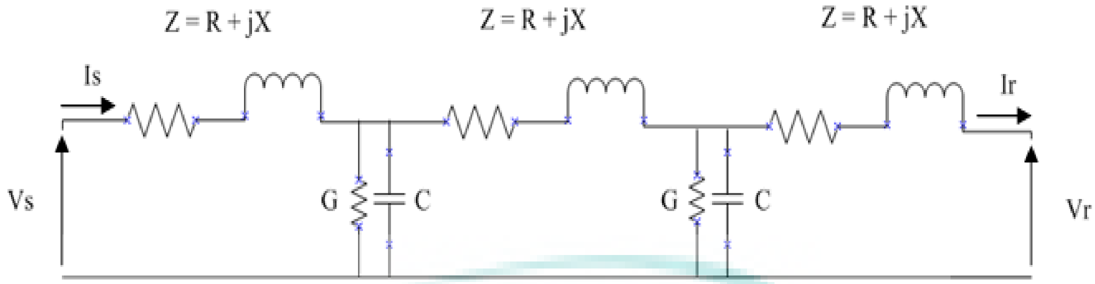

Figure 2.3 Long transmission line

There are many research have been conducted in power system In recent work, to detect voltage sag in power system Alrawashdeh has created an adaptive Kalman Filter (Alrawashdeh, 2014). Besides, in radial distribution system when it comes to improve voltage profile, Azri and Razak have proposed an artificial intelligence approach to obtain optimal total line loss reduction and total cost of capacitor (Azri & Razak, 2014) whereas in non radial distribution system, Particle Swarm Optimization (PSO) was suggested by Hakimi *et al.* to find the optimal capacitor placement (Hakimi, Zarringhalami, & Tafreshi, 2010). Most of the research focuses on radial system and there is no research in parameters estimation in real transmission and distribution line. So, this research focuses on parameters estimation in real transmission line and distribution line. The standard parameter from real transmission line and distribution line which are Midland, England transmission line and UMP distribution line has been used. The comparison between actual parameter values are also taken into account.

2.3 Power transfer in transmission line

Power transfer in transmission line is a main component of an electrical power system. In this perspective, lower power availability to consumers is not a new issue. In 2006, according to Manuel Reta Herna´ndez, it is a major function of transmission line to send out electrical energy with minimal losses from the power source to the load centre (Reta-herna, 2006). However, power generated in the power stations will pass through large and complex network like transformers, cable, overhead line and other equipment and reaches at the end users (Liu, Lin, Cao, & Xu, 2010). It is fact that the unit of electrical energy generated by power station does not match with the units distributed to the consumers. Due to this condition some percentage of units is lost in the distribution network and it will affect the reliability of power transfer in transmission line (Mustafa, 2010) (Ancheng et al., 2016).

There are two types of electrical losses in power systems which are technical losses and non-technical losses (Navani, Sharma, & Sapra, 1956; P. J. Navani, 2009). Technical losses are due to physical properties of the components in the power system whereas non-technical losses are due to actions of external to the power system or caused by loads (Refou, Alsafasfeh, & Alsoud, 2015). Richa and Sh. Vivek stated that changing loads and atmospheric conditions are unpredictable factors which may cause an oscillation of power transfer in transmission line (Kumar & Dhiraj, 2012). Apart from the uncertainties listed, parameters in the transmission line such as R, L and C plays an important role, where the power transfer of transmission line can be improved (Reta-herna, 2006).

There are numerous benefits to be gained through the reduction of losses in power system such as reducing demand charges, improving voltage of a system and increasing load carrying capabilities in the existing circuit (Shicong, Jianbo, Huadong, & Yongjin, 2011). A lot of research has been conducted on the analysis of losses in transmission line. Sin Suphun *et al.* studied the use of optimal power flow based on swarm intelligences to minimize loss (Sinsuphun, Leeton, & Kwannetr, 2011). Bagriyanik *et al.* searched the optimum power system operating conditions by using a fuzzy multi-objective optimization and genetic algorithm-based (Bagriyanik, Aygen, Bagriyanik, & Member, 2003). Utilizing the formulae of corona losses and ohmic characteristics, a mathematical model is designed by Oke and Bamigbola for power losses on transmission lines (Oke & Bamigbola, 2013). These researchers uses design and construction technique, optimal power flow based on swarm intelligences and evolutionary methods to emphasis the system loss reduction.

For this research, a mathematical model has been proposed and the model was simplified from a complex circuit. Kalman Filter method was used as a technique to estimate the parameter values in the system.

2.4 Parameter in transmission line

It is fundamentally important to acquire the precise knowledge of parameters in power transmission line since it is the most useful and practical way to transmit electricity in the power system (Hill, 2004). For a typical transmission line, the following data indicates the geometric information that influences the characteristic line parameters.

Table 2.1 Characteristic transmission line parameters

Element	**Explanation**
Conductor	The body part of the transmission line which can carry electricity along its length. The major characters of conductors include: wire size, conductor material, area of conductor, number of aluminum strands, number of steel strands, number of aluminum layers, DC resistance, AC resistance, inductive reactance and capacitive reactance.
Tower configuration	Steel tower to support an overhead power line. The values of the tower configuration are the following: tower height, conductor spacing, phase spacing and conductors per bundle.
Line Length	The distance of the transmission line. The units are miles when using English system, or kilometers when using the Metric (SI) system.
Power Base	The system power base in MVA.
Voltage Base	The line-line voltage base in KV.
Impedance Base	The impedance base in Ohms. This value is computed when the power base and the voltage base are entered or modified.
Admittance Base	The admittance base in Siemens. It is also computed as the inverse of the impedance base.

2.5 Kalman Filter in power system

Kalman Filter is a set of mathematical equations that provides a method to estimate the state of a process in a way to minimize the mean square error (Saikia & Mehta, 2016). The filter is initializing with an initial estimate of the system and its covariance, the measurement is use to update and refine the estimation (Pagani, Manzoni, & Quarteroni, 2016) (Wong, 2013) (Maklouf, Halwagy, Beumi, & Hassan, 2009). The update system is improved by using new measurement data until a steady state is achieved where no further improvement is obtained.

In energy management system, power system state estimation is important. In previous paper, Larsson and Rehtanz used Kalman Filter to detect the dominant frequency and damping of oscillations during normal operation of the power system (Larsson & Rehtanz, 2003). Vadirajacharya and Lonere proposed state estimation (SE) technique to find unknown values of the state variables based on some imperfect measurement in a system (Vadirajacharya & Lonere, 2015). Wiltshire *et al.* applied Kalman Filtering technique for detection of modal changes in large interconnected power systems (Wiltshire et al., 2007). The technique is tested on both simulated and real data obtained from power system in a normal operation. However, these researches did not states the significant of the indicators (RXB and RLC) that give a great influence to the system involved. Therefore, it is main intention in this research to estimate the parameter values in the system by using Kalman Filter method where an equivalent RLC circuit and its parameters will be used. The Kalman Filter algorithm will be examined in the next section.

2.6 Kalman Filter algorithm

The system has p inputs, n state variables and m outputs. All the variables are matrices and shown in Table 2.2 below.

Table 2.2 Matrix variable

Variable	**Scalar**	**Matrix**	**Matrix size**
State	x_j	x_j	n by 1
Input	u_j	u_j	p by 1
Output	z_j	z_j	m by 1
State gain	a	A	n by n
Input gain	B	B	n by p
Output gain	h	H	m by n
Process noise	w_j	w_j	n by 1
Process noise covariance	Q	Q	n by n
Measurement noise	v_j	v_j	m by 1
Measurement noise covariance	R	R	m by m
A priori covariance	P_j^-	P_j^-	n by n
A posterior covariance	p_j	P_j	n by n
Kalman Filter gain	k_j	K_j	n by m

In the power system model under consideration the state and output equations are (Wiltshire et al., 2007) (Larsson & Rehtanz, 2003)(Alrawashdeh, 2014)(Saikia & Mehta, 2016)

$$x_j = Ax_{j-1} + Bu_j + w_j \qquad 2.1$$

$$z_j = Hx_j + v_j \qquad 2.2$$

The corresponding block diagram is shown below

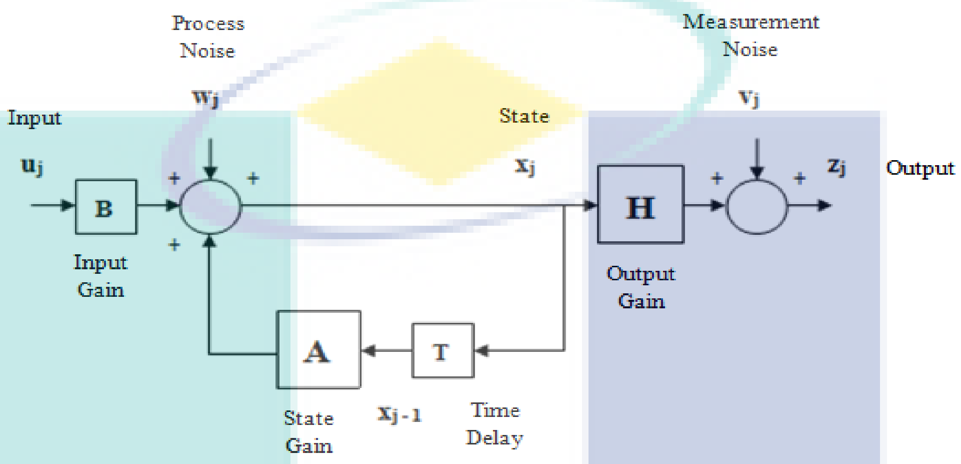

Figure 2.4 Corresponding block diagram

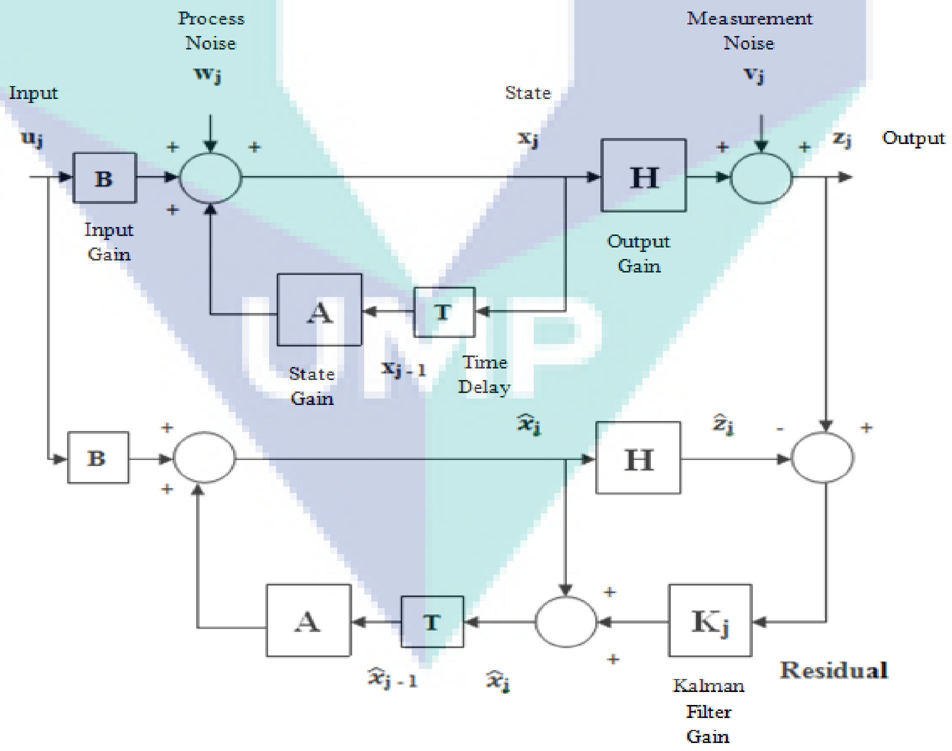

Figure 2.5 Block diagram of Kalman Filter

The predictor equation is given by (Wiltshire et al., 2007)(Larsson & Rehtanz, 2003)(Alrawashdeh, 2014)(Saikia & Mehta, 2016)

$$\hat{x}_j = A\hat{x}_{j-1} + Bu_j \qquad 2.3$$

The corrector equation is given by

$$x_j = x_j + K_j + \left(x_j - H\hat{x}_j\right) \qquad 2.4$$

The priori and posteriori covariances are given by (Wiltshire et al., 2007)(Larsson & Rehtanz, 2003)(Alrawashdeh, 2014)(Saikia & Mehta, 2016)

$$P_j = E\{e_j e_j^T\} = E\left\{(x_j - \hat{x}_j)(x_j - \hat{x}_j)^T\right\} \qquad 2.5$$

where, the superscript ^{T} denotes the matrix transpose.

The best value for the filter gain, K_j, is find by differentiate the a posteriori covariance and set it to zero:

$$\frac{\delta P_j}{\delta K_j} = \frac{\delta E\left\{(x_j - \hat{x}_j)(x_j - \hat{x}_j)^T\right\}}{\delta K_j} \qquad 2.6$$

The Kalman Filter gain is obtained after much algebra and is given by

$$K_j = \frac{P_j H^T}{HP_j H^T + R} \qquad 2.7$$

2.7 Least Square method

The *Least Square* method is a form of mathematical regression analysis that finds the line of best fit for a dataset, providing a visual demonstration of the relationship between the data points. Each point of data is representative of the relationship between a known independent variable and an unknown dependent variable. This method has been used widely to find or estimate the numerical values of the parameters to fit a function to a set of data and to characterize the statistical properties of estimates. . *Least Square* method was first introduced in 1974 by Galileo and French mathematician known as Legendre in 1805 whose exposed the technique by using modern tactic (Abdi, 1974). In previous paper, Wang *et al.* used *Least Square* method in state estimation from theory including weighted *least square* method, fast decoupled method and equivalent current measurement transformation method (Wang, Tian, Hu, & Fan, 2015). This method exist in several variations such as *Ordinary Least Squares* (OLS) for simpler version and *Weighted Least Squares* (WLS) for complicated version (Abdi, 1974). Ray has applied the *Least Square* method to estimate the fundamental frequency in the system (Ray, 2015). Assumed signal model and actual signal square error is reduced to achieve the estimate of frequency. In the modified method a matrix is updated as per the sampling instant (Ray, 2015). The order of this matrix depends on the number of samples being considered. The sentence for Least *Square* algorithm will be presented and discussed in the next section.

2.7.1 Least Square algorithm

Ordinary Least Square is a linear regression, which corresponds to the problem of finding a line that best fits a set of data points. In the standard formulation, a set of N pairs of observations $\{Y_i\ ,\ X_i\}$ is used to find a function relating the value of the dependent variable (Y) to the values of an independent variable (X). With one variable and a linear function, the prediction is given by the following equation (Abdi, 1974) (Ray, 2015):

$$\hat{Y} = a + bX \qquad 2.8$$

This equation involves two free parameters which specify the intercept (a) and the slope (b) of the regression line. The *least square* method defines the estimate of these parameters as the values which minimize the sum of the squares which between the measurements and the model. This amounts to minimizing the expression:

$$\varepsilon = \sum_i \left(Y_i - \hat{Y}_i\right)^2 = \sum_i [Y_i - (bX_i)]^2 \qquad 2.9$$

where ε stands for “error" which is the quantity to be minimized. The estimation of the parameters is obtained using basic results from calculus and, specifically, uses the property that a quadratic expression reaches its minimum value when its derivatives vanish. Taking the derivative of ε with respect to a and b and setting them to zero gives the following set of equations:

$$\frac{\partial \varepsilon}{\partial a} = 2Na + 2b\sum X_i - 2\sum Y_i = 0 \qquad 2.10$$

and

$$\frac{\partial \varepsilon}{\partial b} = 2b\sum {X_i}^2 + 2a\sum X_i - 2\sum Y_i X_i = 0 \qquad 2.11$$

Solving the normal equations gives the following least square estimates of a and b as:

$$a = M_y - bM_x \qquad 2.12$$

with M_x and M_y denoting the means of X and Y and

$$b = \frac{\sum(Y_i - M_y)(X_i - M_x)}{\sum(X_i - M_x)^2} \qquad 2.13$$

Ordinary Least Square can be extended to more than one independent variable by using matrix algebra and to non-linear functions.

2.8 Synchronous Phasor Measurement method

Synchronous Phasor Measurement method is a device that use time synchronization to measures the electrical waves on an electricity (Ivanov, 2009) (Zhao et al., 2015). Time synchronization allows synchronized real-time measurements of multiple remote measurement points on the grid. The resulting measurement is known as a synchrophasor (Kirkham, Dagle, & Ieee, 2014). Recently, synchronized phasor measurement data were proposed to be used as input data to the traditional state estimation model. Phasor measurement units (PMUs) are placed at the buses of transmission substations to measure voltage and current phasors. When compared with other devices, PMUs method produce more accurate results due to the synchronization procedure that use high-speed synchronized sampling with 1 microsecond accuracy (Paula, F.P, 2011). In previous paper, Paula *et al.* proposed a new state estimator including voltage and current phasors and traditional measurements by using Synchronous Phasor Measurement method. With the development of synchronized phasor measurement technology, it helps to improve state estimation performance due to the synchronized characteristics and high data transmission speed (Paula, F.P, 2011). Unfortunately, due to the cost involved, the extensive use of these PMUs will not be instantaneous to use. Lin Lie *et al.* have applied this method to estimate the fundamental voltage and current phasor as well as derived electrical parameters accurately with satisfactory dynamic, and do not suffer from system frequency fluctuation and harmonics even without synchronous sampling (Liu et al., 2010). PMUs attempts to measure the phasor accuracy which can influence on the stability control and protection of system, but also is related to the intelligent dispatching and transmission (Liu et al., 2010). The algorithm for the *Synchronous Phasor Measurement* method will be examined in the next section.

2.8.1 Synchronous Phasor Measurement algorithm

PMU installed at a network bus can measure not only the voltage phasor of this bus, but also the current phasor in the lines connected to that bus as shown in Figure 2.6 below.

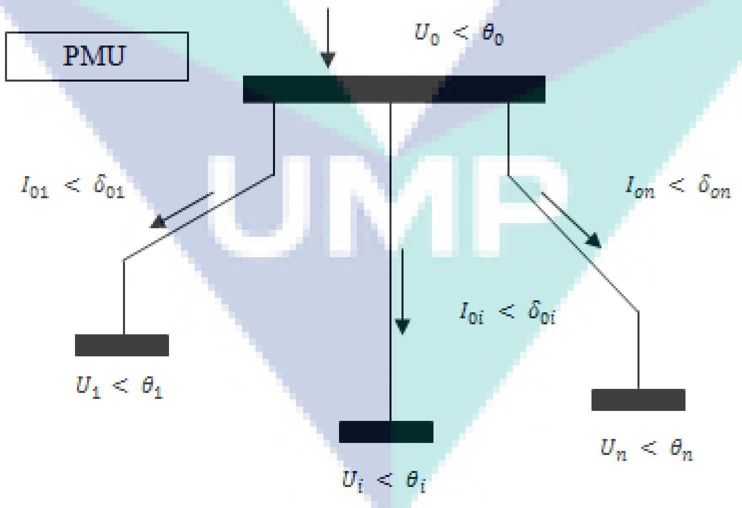

Figure 2.6 Single PMU measurement model

Current phasor measurements can be included in the state estimation model using the rectangular representation $I_{ik} = C_{ik} + j \,.\, D_{ik}$ where:

$$C_{ik} = (g_{i0} + g_{ik}) \,.\, U_i \,.\cos\theta_i - (b_{i0} + b_{ik}) \,.\, U_i \,.\sin\theta_i - g_{ik} \,.\, U_k \,.\cos\theta_k + b_{ik} \,.\, U_k \,.\sin\theta_k$$

$$\mathrm{D}_{ik} = (g_{i0} + g_{ik}) \,.\, U_i \,.\sin\theta_i + (b_{i0} + b_{ik}) \,.\, U_i \,.\cos\theta_i - g_{ik} \,.\, U_k \,.\sin\theta_k - b_{ik} \,.\, U_k \,.\cos\theta_k \quad 2.14$$

where g_{ik}, b_{ik} is a real and imaginary parts of admittance of branch *i* while *k*, g_{i0}, b_{i0} is a real and imaginary parts of shunt admittance for bus *i*.

2.9 Chapter summary

In this chapter, a review of literatures is given and some studies were used as references to complete this research. Motivated by those findings, Kalman Filter is chosen as a main method for the estimation of impedance parameters. Compared to the other method such as *Least Square* method and *Synchronous Phasor Measurement* method, Kalman Filter method is a method that gives more benefits compared to the others where Kalman Filter is low maintenance, fast response time and more accurate. Estimation of parameters impedance took place by using Kalman Filter method which can measure data accordingly and also can save the time. Below is the comparison between Kalman Filter methods with other methods. The lack of the methods causes Kalman Filter to be chosen as the main method for this research.

Table 2.3 Comparison between Kalman Filter methods with other methods

Methods	**Explanation**	**Advantages and disadvantages**
Kalman Filter	This is a statistical technique that adequately describes the random structure of experimental measurements. This filter is able to take into account quantities that are partially or completely neglected in other techniques (such as the variance of the initial estimate of the state and the variance of the model error) (Rampelli & Jena, 2016). The Kalman Filter is well suited to the online digital processing. Its recursive structure allows its real-time execution without storing observations or past estimates.	Advantages: - Ability to correct itself and take the advantage of corrections between unknown phenomena and update itself - Kalman Filter does not require a memory because it does not keep any history other than the previous states - Works perfectly for solving linear problems - Minimizes the unknown error in the system

Table 2.3 Continued

Methods	Explanation	Advantages and disadvantages
		- Low cost Disadvantages: No real problem is linear
Least Square	This technique is very easy to explain and to understand. It is the maximum-likelihood solution and if the Gauss-Markov conditions apply this is the best linear unbiased estimator. But some statistics test might be unreliable when the data is not normally distributed.	Advantages: - Relatively easy to compute, requiring only a squaring and summing for each of the data points - the best fitting straight line to each of the data points - Minimizes the total error in the system Disadvantages: - Sensitivity to outliers - Minimise a squared norm so if outlier is present this can adversely affect results - Requires to invert the sample covariance matrix, $X^T X$, which may not be possible
Synchronous Phasor Measurement	Each phasor measurements is time-stamped according to the universal time standard, so measurements taken by PMUs in differing locations or with different owners can all be synchronized and time-aligned. This lets synchrophasor measurements can be combined to provide a precise and comprehensive view of an entire interconnection (Brussels, 2008). Monitoring and analysis of these measurements let observers identify the changes in grid conditions, including the amount and nature of stress on the system, to better maintain and protect the grid reliability. This technique also implements and evaluates remedial actions to protect system reliability. But consistent performance required for a multi vendor PMU system.	Advantages: - Enables wide area protection and control applications - Provide highly reliable capture of data for critical control functions and postmortem analysis during fault and disturbances - An integrated large, full color display, provides real-time visualization and control of the protected bay Disadvantages: - High investment requirement - Communication delays which leads to delay in generating proper control signal - Low frequency oscillation monitoring

CHAPTER 3

METHODOLOGY

3.1 Chapter overview

Methodology is one of the most important elements to demonstrate how the research is being conducted to achieve all the listed objective. It focuses on the method used during the whole project which attempts to design the Kalman Filter for transmission line. This chapter also presents briefly about the other two techniques suggested by preceding researcher for transmission line estimation i.e *Linear Least Square* method and *Synchronous Phasor Measurement*. The proposed method is developed and then analyzed in MATLAB Simulink software.

3.2 Research development

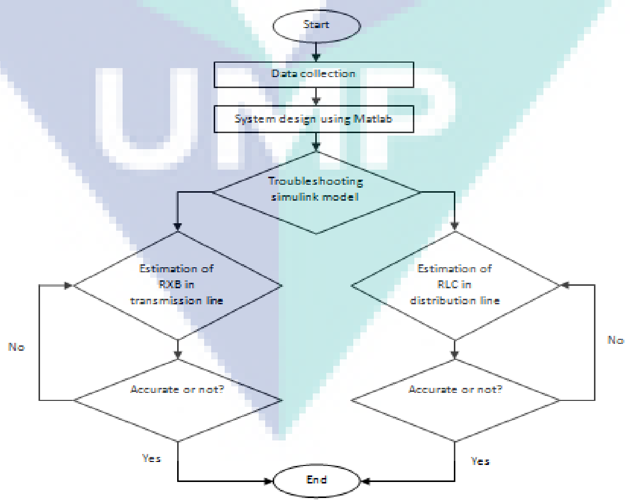

Figure 3.1 Flow chart of project development

Figure 3.1 below show the process flow of the project progress until the project is completed. Initially, as a part of the research planning process, review of several articles and research papers pertaining to this topic was done. This is purposely to understand and grasp an overview of the research problems and for gap analysis. This research is then continues with the system design by using MATLAB simulink. Any associated or relevant issues encountered during the design process will be troubleshooting accordingly with reference to the transmission data set and the Kalman Filter algorithm. Particularly, if there is an error identified, then the system needs to be re-assessing again. The estimation of RXB and RLC values using Kalman Filter method will be continued if there are no errors during the simulation. If the expected RXB and RLC values and the expected efficiency are not achieved, this process will be continuously repeated to gain better result. The simulation will be finishing completely if all of the required conditions are satisfied.

3.3 Data collection

The data from IEEE journal papers is collected and the values of each parameter in Midland, England are recorded and shown in Table 3.1. Previous findings stated that the data have been used in estimation of RXB values by using *Least Square* method and *Synchronous Phasor Measurement* method. Therefore the same data will be used in estimation by using our proposed technique which is Kalman Filter method. The results from these three methods will be analyze and the comparison of performances specifically on errors between these three methods are conducted.

Apart of the transmission line analysis, for system design consistency evaluation, as a case study, data from UMP distribution line also has been recorded to estimate the value of RLC values. The data is obtained from UMP Department of Property Management and Development. The related parameters are presented in Table 3.2. The results from the estimation of RLC values will be compared to the calculated data.

Table 3.1 Parameter value in Midland, England (Ritzmann et al., 2016)

Parameter	**Value**
Voltage, V	400 kV
Frequency, Hz	50 Hz
Resistance, R	2.96 Ω
Reactance, X	32.40 Ω
Susceptance, B	3.69 x 10^{-4} S

Table 3.2 Parameter value in UMP

Parameter	Value
Voltage, V	11 kV
Frequency, Hz	60 Hz
Current, A	220.73 A
Resistance, R	46.35 Ω
Inductance, mH	48.58 mH
Capacitance, F	0 F

3.4 Kalman Filter technique

Kalman Filter has been commercially used for system estimation and it has become one of the popular methods to examine system accuracies. Therefore, in this research, the application of the Kalman Filter technique was applied. Until the day this thesis is written, this approach is still new and can provide alternative yet competent results. Many researchers have found that the Kalman Filter has given them a better result in the process of estimation. Therefore, this research will apply the Kalman Filter technique to eliminate noise and obtain a better correlation in order to be able to update and predict the sample of observed. The algorithm works by consistently predict and update the results by referring to the previous data as an initial estimation. This is actually a characteristic in Bayes Rule which attempts to predict the results from time to time by only based on previous information. The difficult part in this research is to tolerate any noise and to obtain a better correlation of estimation accuracy with the related parameters data. The noise is modelled based on the assumption that it contains uncertain information which the system unable to control such as the electronics component tolerant, wire size and wire type. The noise model is kept low and adjusted based on the reference data obtained from Midlands, England.

In Kalman Filter, the technique was developed by constructing a linear equation containing the entire data sample. All the data used was stated and applied into the *Least Square* method. Table 3.3 below shows the Kalman Filter algorithm that had been used to build this modelling.

Table 3.3 Kalman Filter algorithm

Element	Equation
Model	$\bar{x}(k+1) = G\bar{x}(k) + H\bar{u}(k) + \bar{w}(k) \quad \bar{w}(k) \sim N(0, R_w)$ $\bar{y}(k) = C\bar{x}(k) + \bar{v}(k) \quad \bar{v}(k) \sim N(0, R_v)$
Initialize	$\bar{x}(0\|0) = \hat{x}_0 \ and \ P(0\|0) = P_0$
Gain	$K(k+1) = P(k+1)C^T [R_v + CP(k+1\|k)C^T]^{-1}$
Measurement	$\hat{x}(k+1\|k+1) = \hat{x}(k+1\|k) + K(k+1)[\bar{y}(k+1) - C\hat{x}(k+1\|k)]$
Update	$P(k+1\|k+1) = P(k+1\|k) - K(k+1)CP(k+1\|k)$
Propagation	$\hat{x}(k+1\|k) = G\hat{x}(k\|k) + H\bar{u}(k) \ State \ update$
(Time update)	$P(k+1\|k) = GP(k\|k)G^T + R_w \ Covariance \ update$

3.5 Data analysis

The values of RXB and RLC that have been collected and calculated will be used to differentiate and analyze between real values in the system and the computed values in MATLAB simulink. The comparison of RXB estimation values by using Kalman Filter in Midland, England will be compared to the other two methods which are *Least Square* method and Synchronous method. Then, the performances regarding the parameter errors also will be taken into consideration. To support the Kalman Filter capability for estimation purposes, a case study the Kalman Filter based estimation of RLC values for distribution line is then presented and compared with the real values from Department of Property Management and Development in UMP. All of the above analyses are constructed to determine and prove the reliability of Kalman Filter method on these two estimations of RXB and RLC.

3.6 MATLAB simulink

As a computational method, MATLAB provides an interactive environment with hundreds of reliable and accurate built-in mathematical functions. These functions provide solutions to a broad range of mathematical problems including matrix algebra, complex arithmetic, linear systems differential equations, signal processing, optimization, nonlinear systems, and many other types of scientific computations. The most important feature of MATLAB is its programming capability, which is very easy to learn and to use, and which allows user-developed functions (Folarin, Sakala, Matlotse, & Gasennelwe-jeffrey, 2018).

For this research, MATLAB software is used and the Kalman Filter model is designed by using MATLAB simulink. From this model the simulation can be done. The graph will show the estimation values of R, L and C. If the estimation graph obtain from the simulation is almost the same with the raw data, it shows the system is more accurate. The block diagram of Kalman Filter that has been designed is shown as follow.

3.6.1 Development of Kalman Filter

The general Kalman Filter modelling is designed by using MATLAB simulink is shown in Figure 3.2 below.

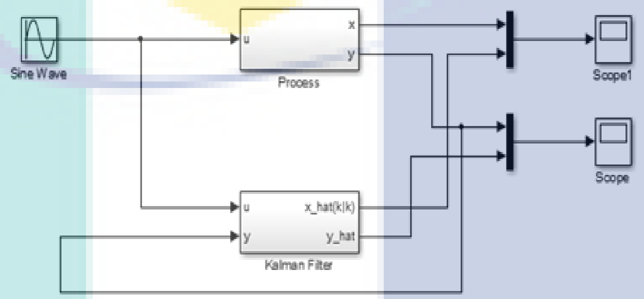

Figure 3.2 General model of Kalman Filter

Circuit for process block is shown in Figure 3.3 below.

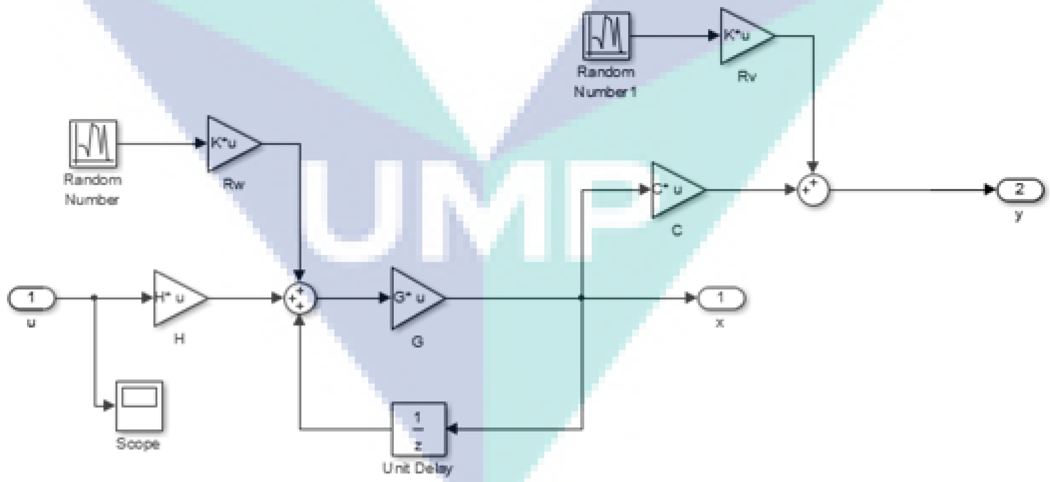

Figure 3.3 Process block

Circuit for Kalman Filter block is shown in Figure 3.4 below.

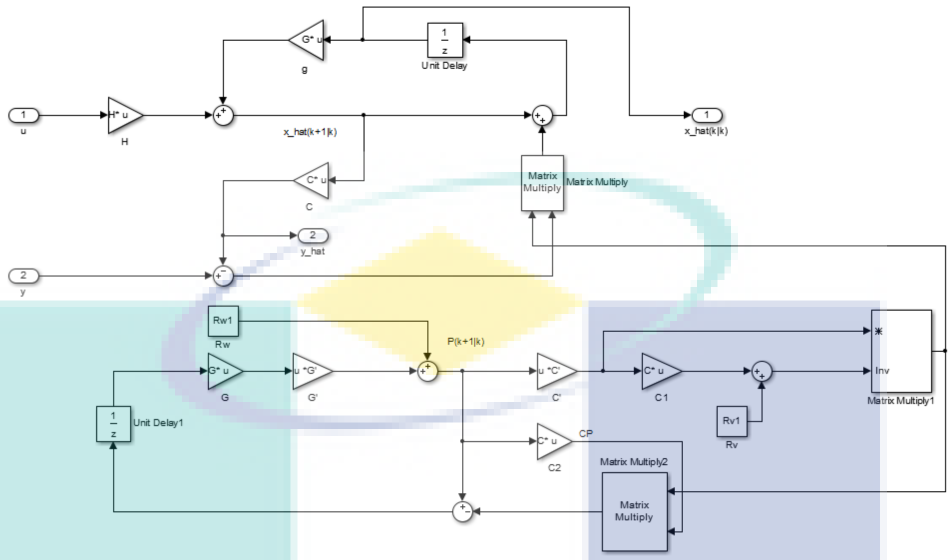

Figure 3.4 Kalman Filter block

3.6.2 Parameter setting for simulation

All the parameter was created in the m file. The parameter can also be created by clicking the view button on the top of the simulink. Click the Model Explorer icon and choose the Model Workspace. After that, change the data source into MATLAB code to insert the parameter as shown in the Figure 3.5 below.

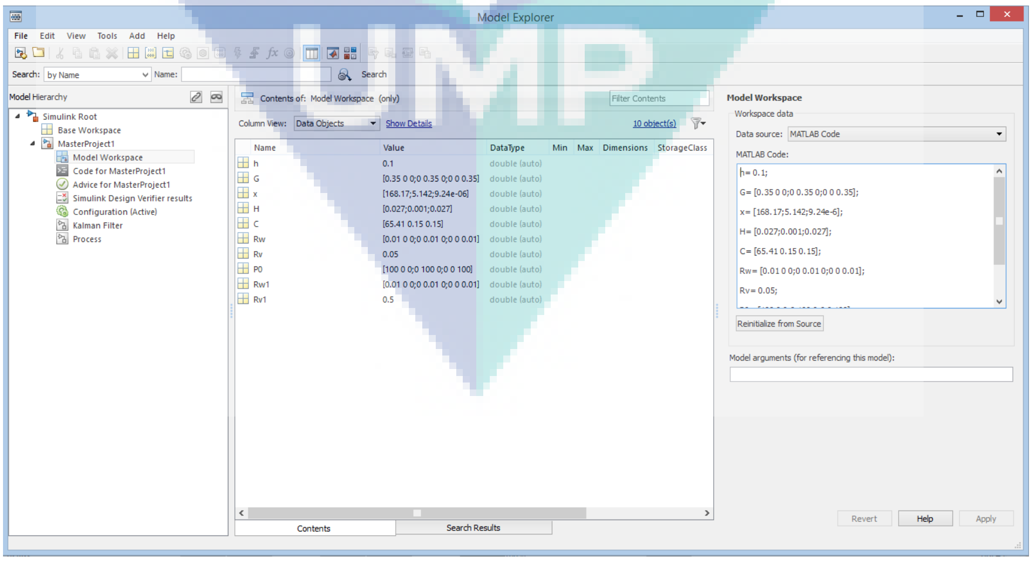

Figure 3.5 Parameter insertion

For a linear system, the process model of Kalman Filter is described as

$$X_k = AX_{k-1} + BU_k + W_k \tag{3.1}$$

$$Z_k = HX_k + V_k \tag{3.2}$$

where X_k is the estimation value of X, $X_{(k-1)}$ is the estimate value on the previous state, U_k is the control input, W_k and V_k is noise covariance matrix, A, B and C will be numerical constant (Alazard, 2011).

The estimation value of X_k is represented by R, X and B as

$$X_k = \begin{bmatrix} R \\ X \\ B \end{bmatrix} \tag{3.3}$$

where R is resistance, X is reactance and B is susceptance. In this study, current, A is used as a control input, U_k.

$$U_k = \begin{bmatrix} A & 0 & 0 \\ 0 & A & 0 \\ 0 & 0 & A \end{bmatrix} \tag{3.4}$$

The estimated value on the previous state, $X_{(k-1)}$ is represented by

$$X_{k-1} = \begin{bmatrix} R_{k-1} \\ X_{k-1} \\ B_{k-1} \end{bmatrix} \tag{3.5}$$

Kalman Filter is used to provide an estimation of R, X and B values in the system. Kalman Filter recursively computes estimation for a state X_k according to the process and observation model. The stages of Kalman Filter algorithm are as follows:

- *Prediction* (time update) to estimate priori estimation of state and its error covariance matrix:

$$X_k = AX_{k-1} + BU_k \tag{3.6}$$

$$P_k = AP_{k-1}A^T + Q \tag{3.7}$$

where P_k is prior error covariance. This value is used in the measurement update equations.

- *Correction* (measurement update) to provide correction based on the measurement Z_k to yield the posteriori state estimate and its error covariance:

$$K_k = P_k H^T (H P_k H^T + R)^{-1} \quad 3.8$$

$$X_k = X_k + K_k (Z_k - H X_k) \quad 3.9$$

$$P_k = (1 - K_k H) P_k \quad 3.10$$

where K_k is Kalman gain.

3.7 Chapter summary

In this chapter, the methodology of the study is an important process in a research. This is to explain and to determine whether the objectives can be achieved or not. Effective method of methodology will ensure the establishment of good results, the project meets the objective and the goals of the research. For this research Kalman Filter method has been chosen over the two methods described in this chapter. Kalman Filter was used for estimation of impedance parameters in substation of Midland, England and Universiti Malaysia Pahang. This research started with the development of Kalman Filter model by using MATLAB simulink. Then, the troubleshooting will take place after the system design was completed. This troubleshooting was take place to ensure that this model has no error occur before the real data was set-up. Kalman Filter has the ability to eliminate unknown noises in a system. This will make the estimation of impedance parameters more precisely. This Kalman Filter able to estimate the impedance parameters more accurate compared to the *Least Square* method and *Synchronous Phasor Measurement* method. The objective also has been achieved through the development of Kalman Filter based estimation for RXB and RLC parameter for transmission line in Midland, England and distribution line in Universiti Malaysia Pahang. The evidence of this statement will be discussed in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Chapter overview

This subsection investigates the development of Kalman Filter based estimation for Midland, England transmission line. The proposed design and the results demonstrate the achievement of the first research objective. To evaluate the design, results of having different noise conditions to the estimation of Midland transmission line and UMP distribution line parameter values are examined. Note that the noise is presenting uncertain information about the whole transmission line such as the electrical and electronics parts tolerances, wire size and wire type. Therefore, selections of different noise values are considered to demonstrate those conditions.

4.2 Results and discussion

4.2.1 Transmission line in Midland, England

A single phase of the 400 kV, 102 km long transmission line data located between substations Grendon and Staythorpe, East Midlands, England was used and simulated by using MATLAB simulink (Nur et al., 2017). This section demonstrates how Kalman Filter works to estimate those values effectively by considering the system noises of 0.1 and 10 to simulate the unknown parameters which can affects the estimation results such as size, length and type of cables.

Simulation was conducted for the equivalent circuit of transmission line and tuning process also take place in order to gain converge graph of each parameters of the circuit. Figure 4.1 presents the Kalman Filter model for the transmission line. Figure 4.2, Figure 4.3 and Figure 4.4 depicts the real values of R, X and B which are 2.96 Ω, 32.40 Ω and 3.69 x 10^{-4} S respectively while the values of estimated are 2.95 Ω, 32.42 Ω and 3.64 x 10^{-4} S respectively with the assumption that the system has low noise of 0.1. It can be perceived that there are small differences between the real and new estimation values of R, X and B. The estimated parameters are obtained through averaging and seen approximating to the real values. This shows that the relative error between the real values and estimated values will decrease with the decreasing value of noise. These tangible values represent the benefit from the system. Therefore higher consistency of estimation for R, X and B values calculated based on to the approximate results between real and estimated values.

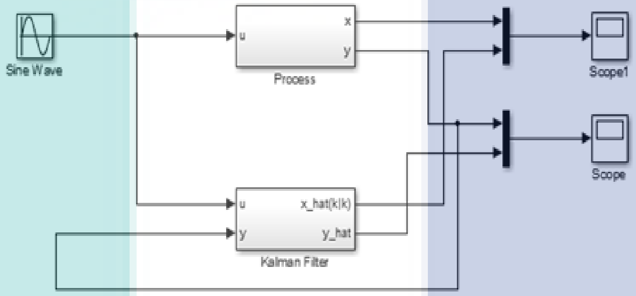

Figure 4.1 Block diagram of Kalman Filter with noise = 0.1

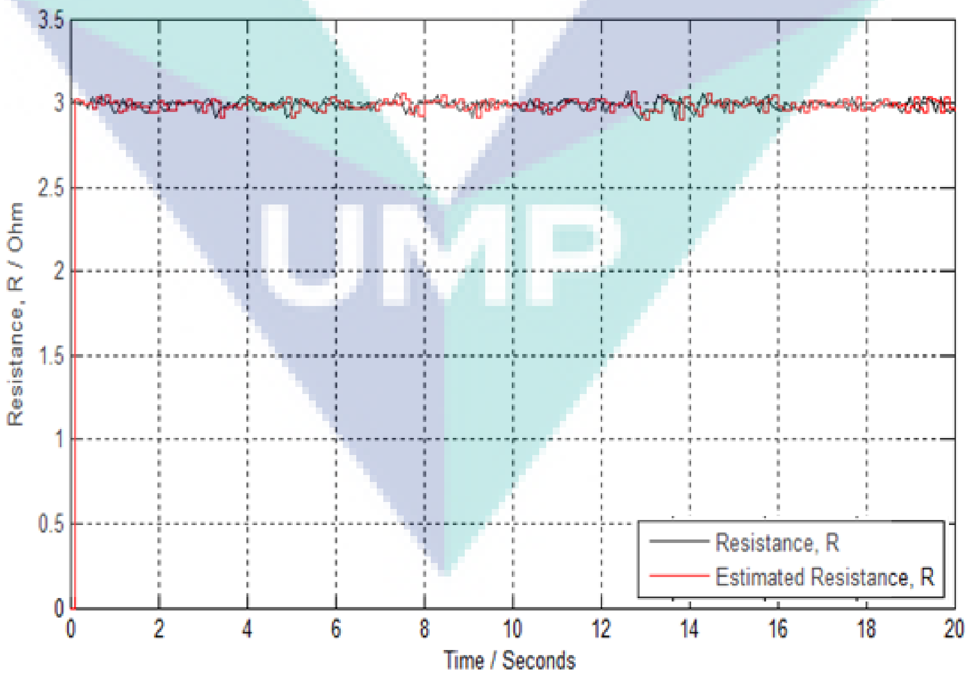

Figure 4.2 Graph of calculated and estimated value of resisteance, R

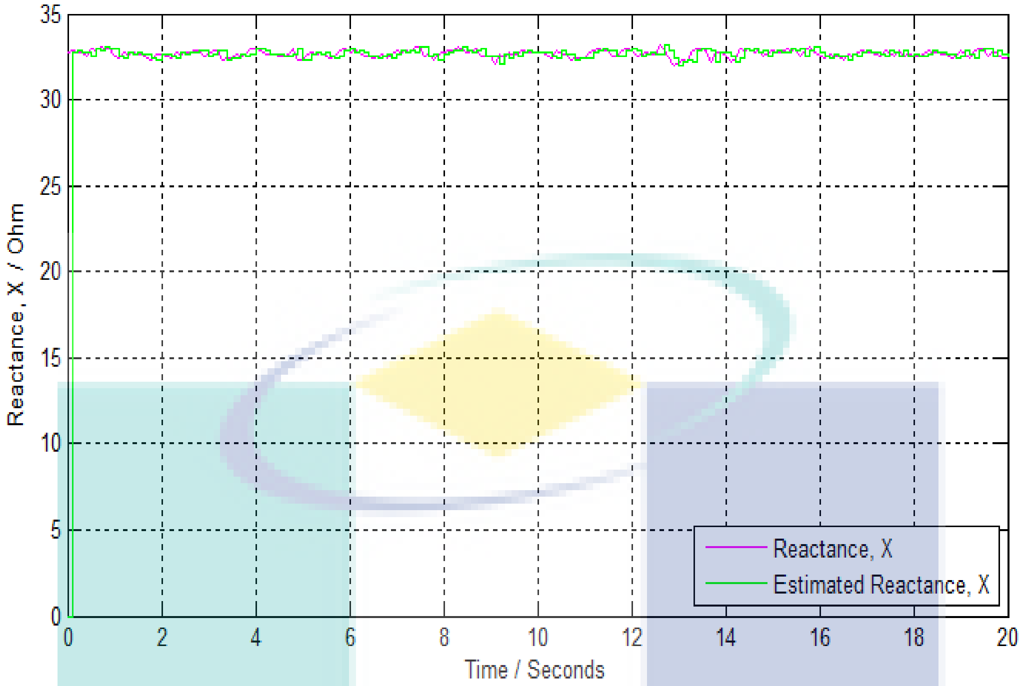

Figure 4.3 Graph of calculated and estimated value of reactance, X

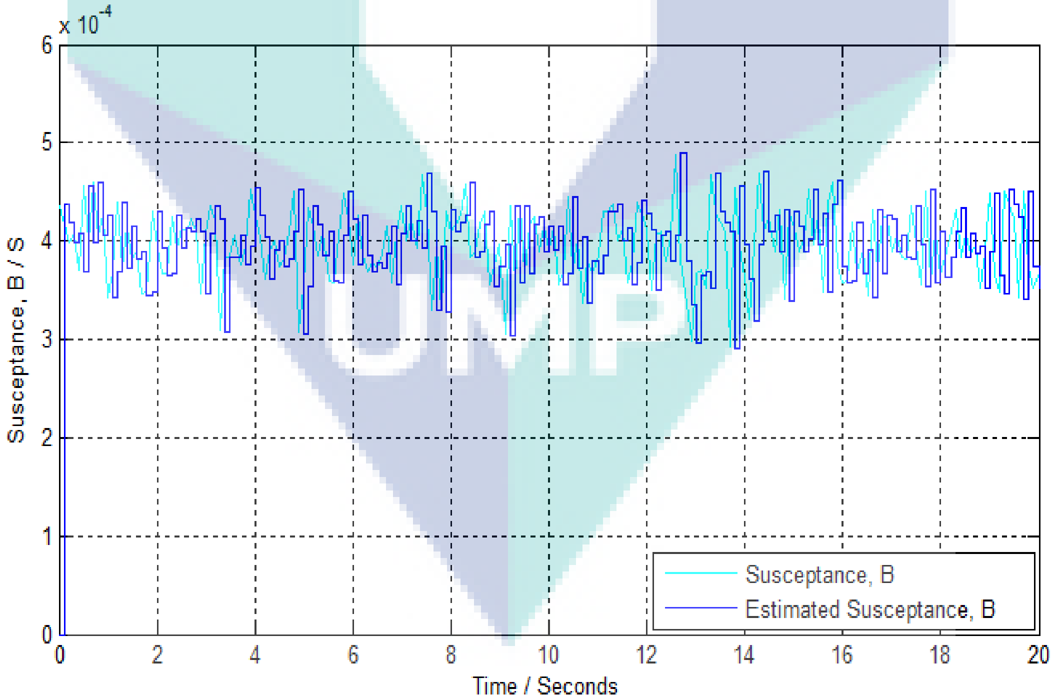

Figure 4.4 Graph of calculated and estimated value of susceptance, B

Figure 4.5 below shows the model of R, X and B by using the Kalman Filter approach in the system considering higher system noise of 10. This is then followed by Figure 4.6, Figure 4.7 and Figure 4.8 which determines that the real values of R, X and B are 2.96 Ω, 32.40 Ω and 3.69 x 10^{-4} S respectively while the estimated values of R, X and B are 2.67 Ω, 33.02 Ω and 2.84 x 10^{-4} S respectively. Both of the calculated and estimated parameters are seen to be having less consistency and the results are slightly becomes worse due to the higher Gaussian noise of the system.

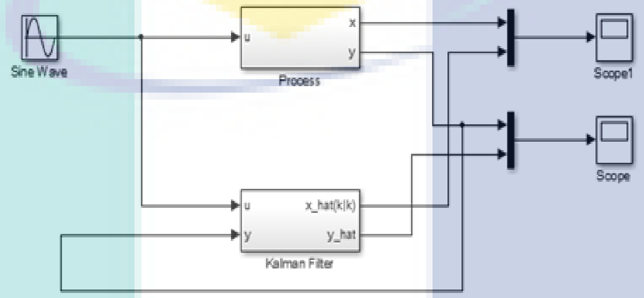

Figure 4.5 Block diagram of Kalman Filter with noise = 10

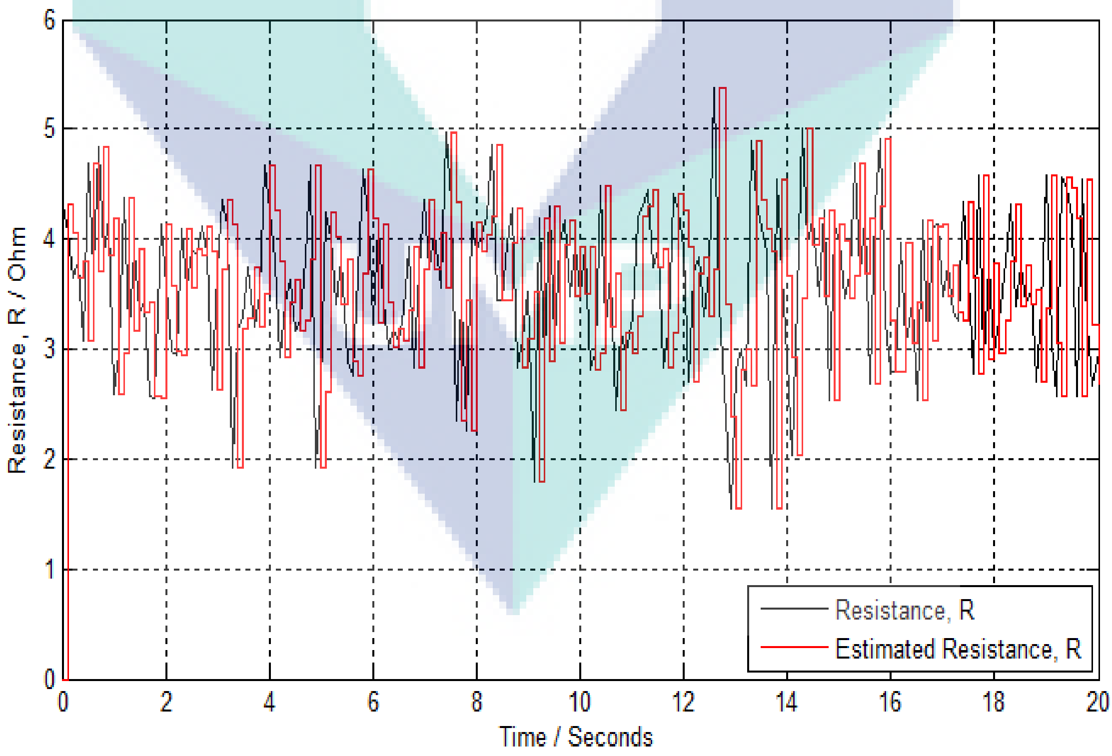

Figure 4.6 Graph of calculated and estimated value of resistance, R

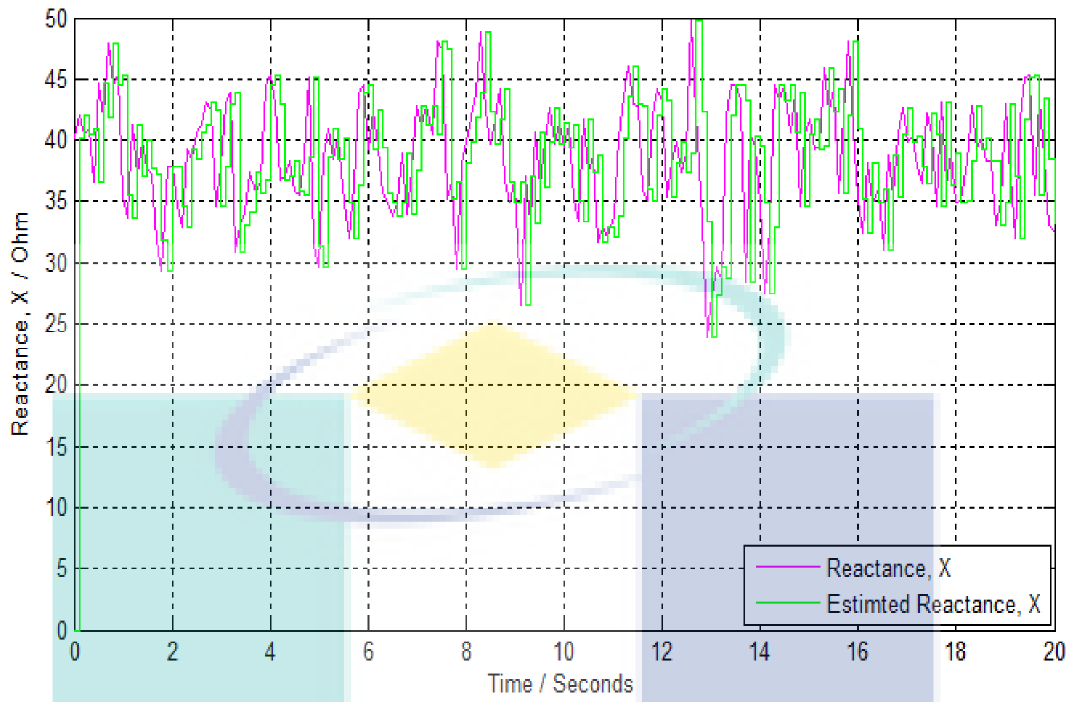

Figure 4.7 Graph of calculated and estimated value of reactance, X

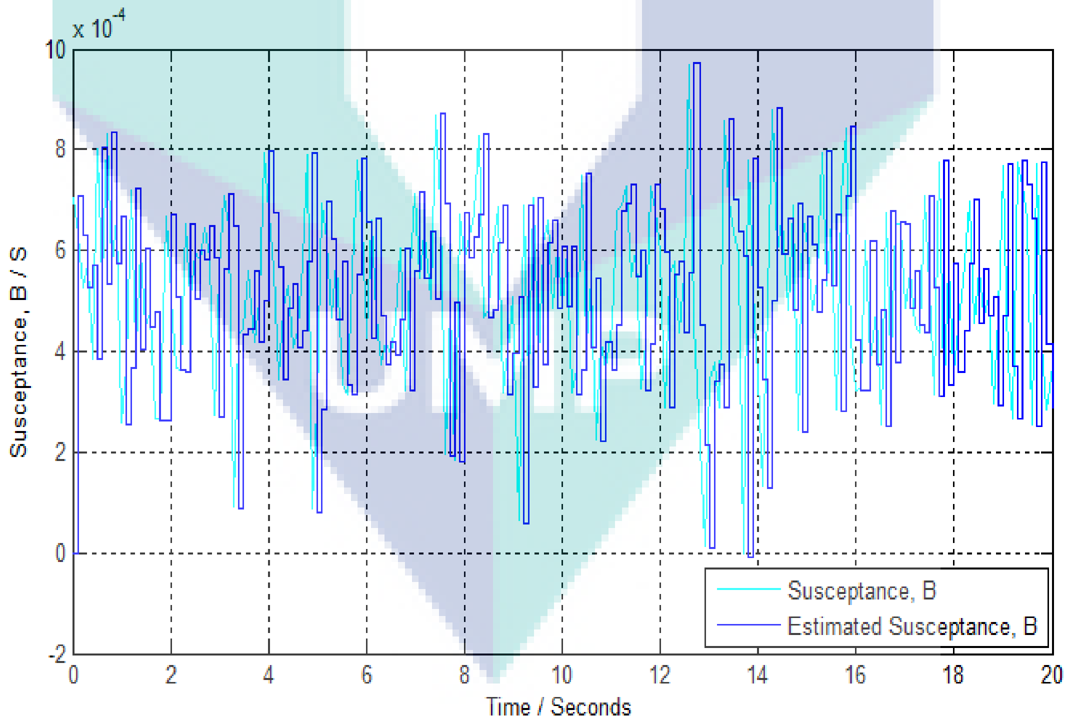

Figure 4.8 Graph of calculated and estimated value of susceptance, B

Table 4.1 defines the system parameter values of the designed Kalman Filter model in simulink with small value of noise which is 0.1. It shows that the accuracy of R, X and B in the system is more accurate and can be viewed by the small percentage value of errors i.e 0.33 %, 0.062 % and 1.35 x 10^{-4} % respectively. This performance is as expected as the system has lower noise thus resulting good estimation accuracy.

Table 4.1 Parameter value with noise = 0.1

Parameter	**Real value**	**Estimated value**	**Percentage of parameter error (%)**
Resistance, R	2.96 Ω	2.95 Ω	0.33
Reactance, X	32.40 Ω	32.42 Ω	0.062
Susceptance, B	3.69 x 10^{-4} S	3.64 x 10^{-4} S	1.35 x 10^{-4}

Table 4.2 defines the system parameters of the simulink model with the greater value of noise which is 50. It shows the accuracy of R, X and B in the system become inaccurate with the greater percentage value of errors which are 10.14 %, 1.91 % and 23.04 x 10^{-4} % respectively. Thus, it is proved that the accuracy in the system will decrease with the increasing noise.

Table 4.2 Parameter value with noise = 50

Parameter	**Real value**	**Estimated value**	**Percentage of parameter error (%)**
Resistance, R	2.96 Ω	2.66 Ω	10.14
Reactance, X	32.40 Ω	33.02 Ω	1.91
Susceptance, B	3.69 x 10^{-4} S	2.84 x 10^{-4} S	23.04 x 10^{-4}

According to Table 4.1 and Table 4.2 as well as based on figures presented previously, the value of noise has significant effect to the accuracy of R, X and B estimation. The higher the value of noises or disturbances in the system, the performance will be degrading. These results of R, X and B estimation indicate the possibility for parameters estimation even in different places. Noted that, it is important to consider that the values of R, X and B directly determines the system efficiency in the transmission line.

As mentioned on the research second objectives, the system is then compared with the available techniques; *Least Square* and *Synchronous Phasor Measurement* approaches. Table 4.3 and Table 4.4 indicate the comparison of parameter values and percentage of parameter errors between Kalman Filter and *Least Square* method and

Synchronous Phasor Measurement method. The line parameter values of R, X and B by using Kalman Filter are 2.95 Ω, 32.42 Ω and 3.64 x 10^{-4} S respectively while the line parameter values of R, X and B by using *Linear Square* method and *Synchronous Phasor Measurement* method are 0.11 Ω, 32.29 Ω, 17.11 x 10^{-4} S and 1.99 Ω, 32.30 Ω, 2.60 x 10^{-4} S respectively, whereas percentage of parameter errors of R, X and B are 0.337 %, 0.062 % and 1.35 x 10^{-4} % respectively while the line percentage of parameter errors of R, X and B by using *Linear Square* method and *Synchronous Phasor Measurement* method are 2.85 %, 0.111 %, 20.8 x 10^{-4} % and 0.974 %, 0.086 %, 1.09 x 10^{-4} % respectively.

Table 4.3 Comparison of parameter values between Least Square, Synchronous Phasor Measurement and Kalman Filter method when noise = 0.1

Parameter values				
Parameter	**Real values**	**Least Square method**	**Synchronous Phasor Measurement method**	**Kalman Filter method**
Resistance, R	2.96 Ω	0.11 Ω	1.99 Ω	2.95 Ω
Reactance, X	32.4 Ω	32.29 Ω	32.30 Ω	32.42 Ω
Susceptance, B	3.69 x 10^{-4} S	17.11 x 10^{-4} S	2.60 x 10^{-4} S	3.64 x 10^{-4} S

Table 4.4 Comparison of percentage parameter errors between Least Square, Synchronous Phasor Measurement and Kalman Filter method when noise = 0.1

Percentage of parameter error (%)			
Parameter	**Least Square method**	**Synchronous Phasor Measurement method**	**Kalman Filter method**
Resistance, R	2.85	0.974	0.337
Reactance, X	0.111	0.086	0.062
Susceptance, B	20.8 x 10^{-4}	1.09 x 10^{-4}	1.35 x 10^{-4}

Generally, from the results presented in Table 4.3 and

Table 4.4 above, Kalman Filter give a higher accuracy compared to the *Least Square* method and *Synchronous Phasor Measurement* method. From these two results of percentage parameter errors, it can be proven that Kalman Filter is a better method that can be used for estimation.

4.2.2 UMP distribution line

As been highlighted in chapter 1 especially on the research objectives, the analysis is also organized by looking into the Kalman Filter performance for UMP distribution line (Nur, Mohd, Ahmad, & Mohamed, n.d.). In UMP, there are no systems used for verifications of the distribution parameters. Currently engineers are only referring to the data provided by consultant. The analysis generally applies does data to examine the UMP distribution line to offer better analysis and references of the electrical usage in the university.

A 11 kV, 5 km long, 60 Hz distribution line is considered. The line parameters of R, L and C are 46.35 Ω, 48.58 mH and 0 F respectively. Capacitance value is considered as negligible due to the short transmission line properties. The line is operated in a power of 3911 kW at receiving end. The following are previous and latest value of parameter estimation by using MATLAB simulink. Other quantities such as active power and impedance are calculated by using Ohms Law shown in equations below.

$$p = \sqrt{3} VI \cos\theta \quad (4.1)$$

$$\cos\theta = 0.93 \quad (4.2)$$

$$V = IZ \quad (4.3)$$

$$Z = 49.84\Omega$$

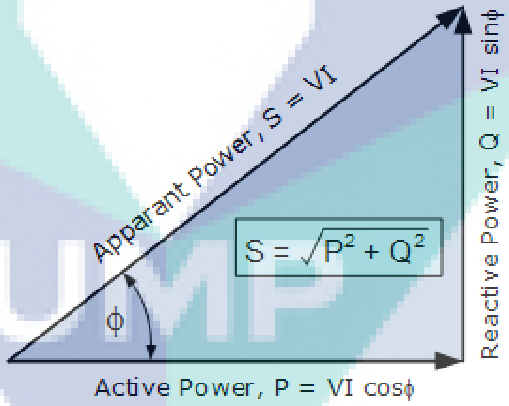

Figure 4.9 Power triangle

$$pf = \cos\theta \quad (4.4)$$

$$pf = \frac{R}{Z} = \frac{P}{S} \quad (4.5)$$

$$R = 46.35\Omega$$

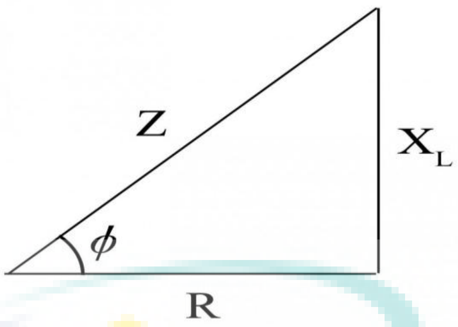

Figure 4.10 Phasor diagram

From the phasor diagram above, it is clear that the equation will be (Ravish R. Singh, 2003):

$$\theta = \tan^{-1}\left(\frac{\omega L}{R}\right) \qquad 4.6$$

It is known that,

$$\omega = 2\pi f \qquad 4.7$$

Substituting all the related value into 4.7, the equation becomes,

$$\omega = 376.99$$

By referring to equation 4.4, the value of pf is substitute to get the value of θ,

$$\theta = 21.5652$$

In order to get the value of L, all the values are substitute into equation 4.6,

$$L = 48.58mH$$

Simulation was conducted for the distribution line to simulate the UMP condition and tuning process also take place in order to achieve a good estimation results. Figure 4.11 and Figure 4.12 below shows the calculated and estimation values of R, L and C over a period. The values of calculated R, L and C simulated by using

Kalman Filter are 46.35 Ω, 48.58 mH and 0 F while the average values of estimated are 46.34 Ω, 48.57 mH and 0 F respectively with noise of 0.1. There are small differences between the previous and new estimated values of R, L and C. Both of the calculated and estimated parameters are seen overlapping with each other due to the approximate parameter values. The result shows the higher consistency involved in R, L and C value due to the approximate results between calculated and estimated values. The value of capacitance is 0 F as it is assumed negligible due to the properties of short transmission line. It must be noted that the initial values of estimation error covariance matrix affects the estimation of parameter values. Figure 4.11 determines the calculated value of resistance in the system which is 46.35 Ω. The red colour lines refer to the estimation value by using Kalman Filter method.

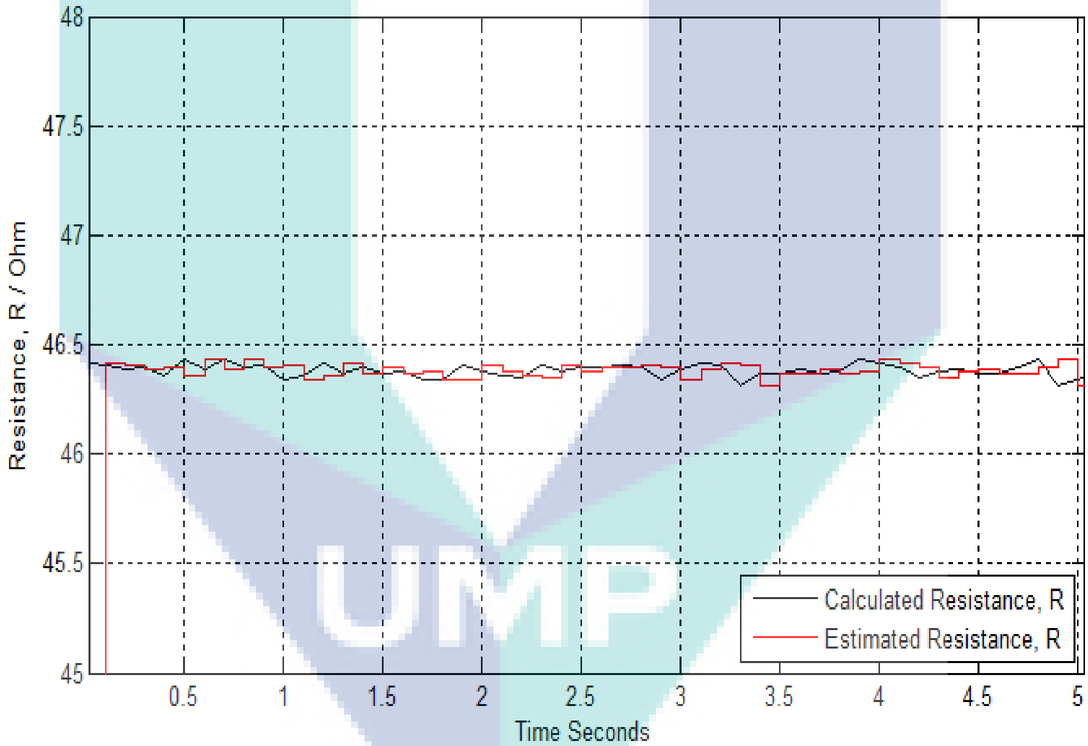

Figure 4.11 Graph of calculated and estimated value of resistance, R

Figure 4.12 demonstrates the calculated value of inductance in the system which is 48.58 mH. The green colour lines refer to the estimation value by using Kalman Filter method.

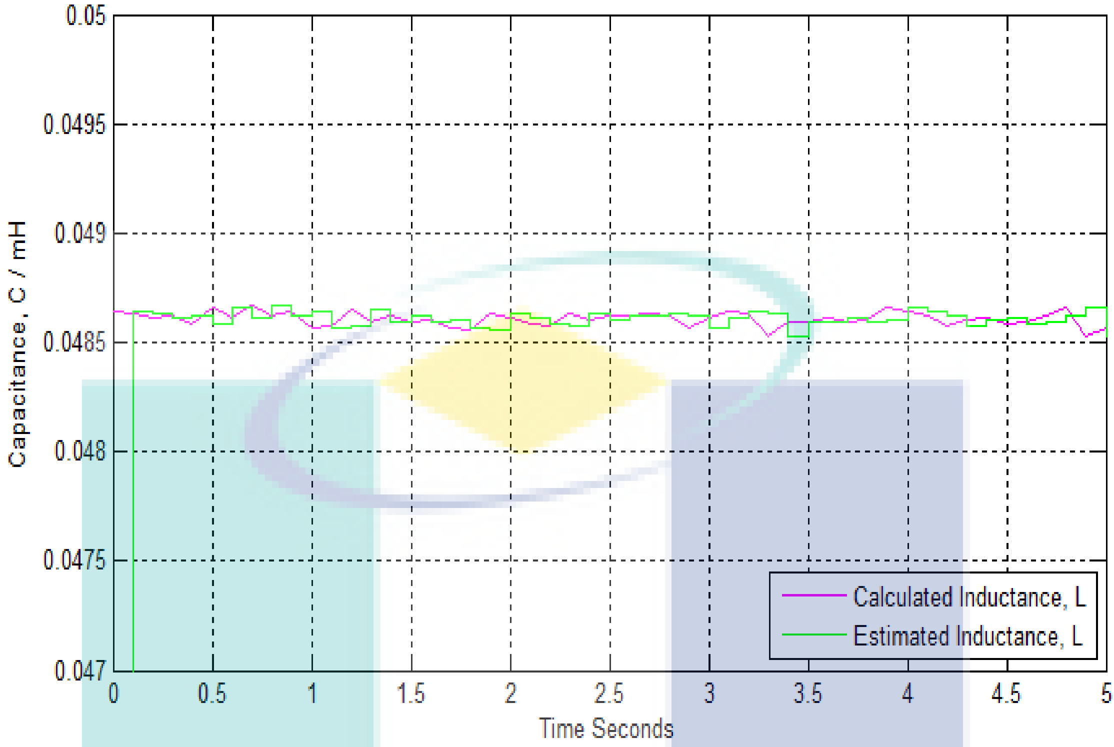

Figure 4.12 Graph of calculated and estimated value of inductance, L

Figure 4.13 and Figure 4.14 below also shows the calculated and estimation values of R, L and C in the system. The calculated values of R, L and C are 46.35 Ω, 48.58 mH and 0 F while the estimated average values of R, L and C are 46.22 Ω, 48.43 mH and 0 F respectively with higher system noise of 10. Both of the calculated and estimated parameters are seen less consistency and the results are slightly different due to the greater noise in the system.

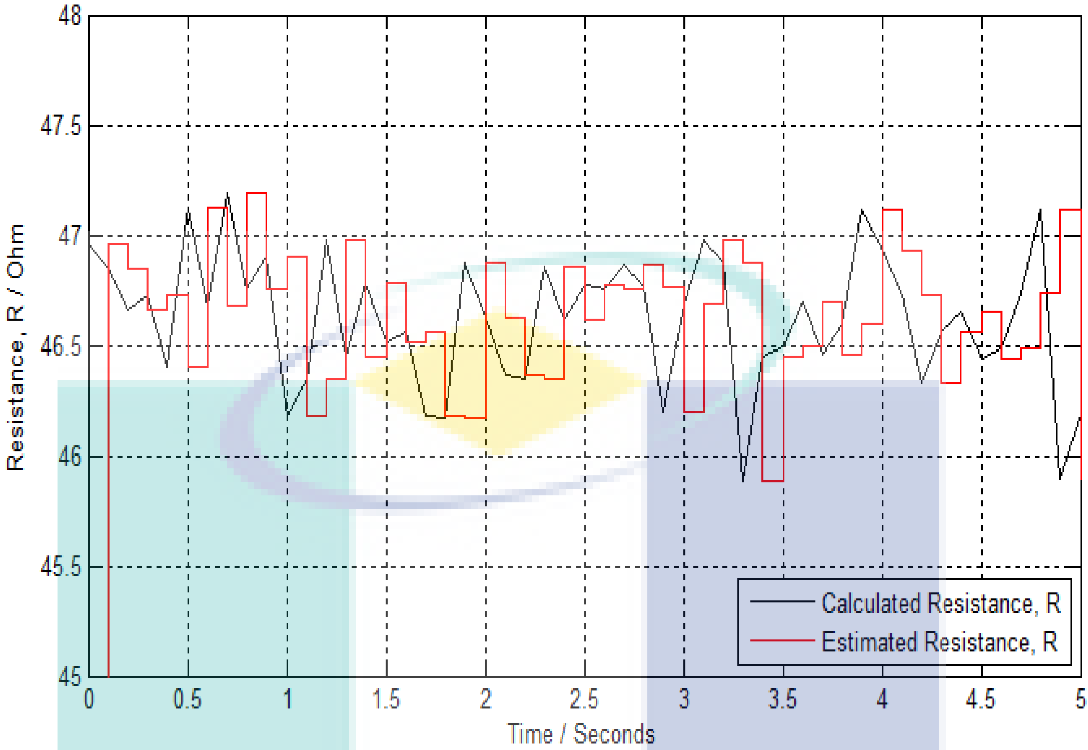

Figure 4.13 Graph of calculated and estimated value of resistance, R

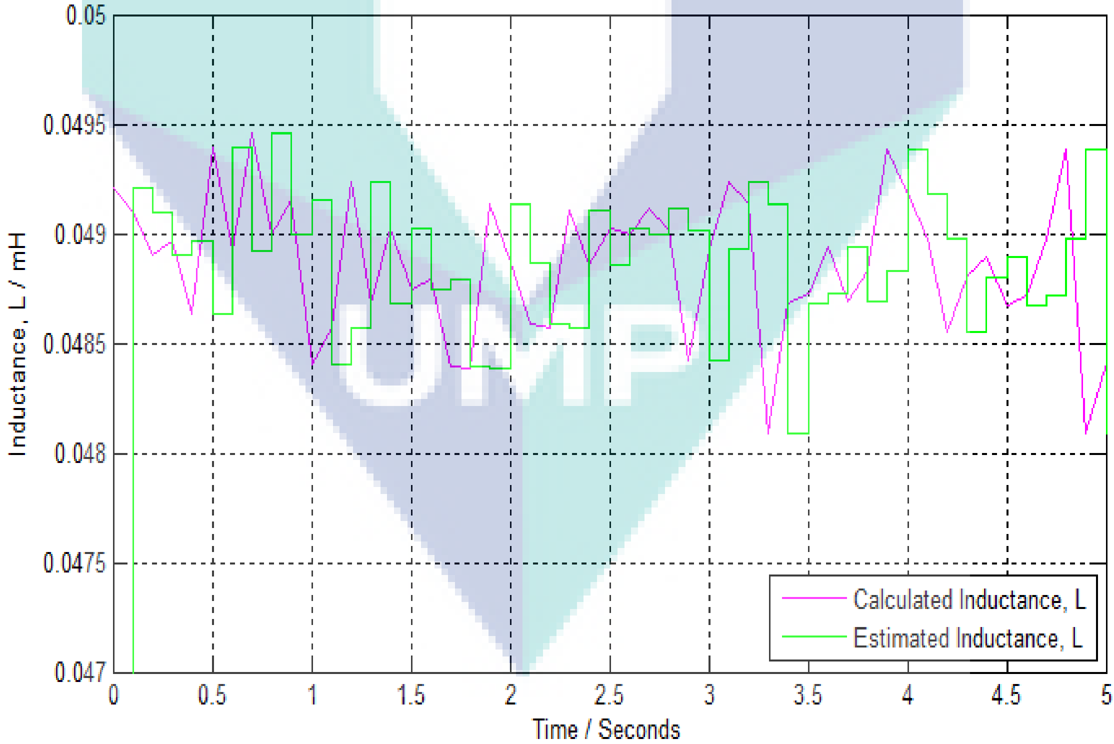

Figure 4.14 Graph of calculated and estimated value of inductance, L

Table 4.5 defines the system parameters of the simulink model with the small value of noise which are 0.1 and 10. It defines that the accuracy of resistance and inductance in the system more precise with the small value of noise which is 0.021 Ω and 0.021 mH respectively. Thus, it is shown that higher estimation accuracy will be achieved with the decreasing values of the noise. This table also considers the system parameters of the simulink model with the greater value of noise which is 10. It shows that the accuracy of resistance and inductance in the system is inaccurate with the greater value of error which is 0.28 Ω and 0.31 mH respectively. Owing to these information, it is proved that the accuracy in the system will decrease with the increasing noise.

Table 4.5 Parameter error

Noise = 0.1			
Parameter	**Calculated value (average)**	**Estimated value (average)**	**Percentage of parameter error (%)**
Resistance, R	46.35 Ω	46.34 Ω	0.021
Inductance, L	48.58 mH	48.57 mH	0.021
Capacitance, C	0 F	0 F	-
Noise = 10			
Resistance, R	46.35 Ω	46.22 Ω	0.28
Inductance, L	48.58 mH	48.43 mH	0.31
Capacitance, C	0 F	0 F	-

According to this table and figures presented, the value of noise affected the accuracy of R, L and C estimation in the system. The higher the value of noises or disturbance in the system, the performance degrades. These results also indicates the possibility to estimate the RLC parameters accurately even in different places especially when the same cable is being used. Higher voltage increased the noise problem in a system. These situations occur due to the electron movement within the electrical circuits. A better accuracy will comes from short transmission line compared to long transmission line. This is due to the unknown noises in which the bigger system will have more unknown noises compared to the small system. From this result of accuracy, it can be proven that Kalman Filter is a better method that can be used for estimation.

Remark that, it is important to consider of R, X and B and R, L and C values as they affected the determination of power transfer, voltage drop and efficiency in the transmission line. The voltage drop in the line depends upon the values of above three lines constant. Similarly, the resistance of transmission line is the most important cause of power losses in the line and determine the transmission efficiency. Same as R, X and B values of R, L and C also affected the determination of efficiency in a system.

4.3 Chapter summary

In this chapter, the results of this research are presented in the form of table and graph. This analysis is important to make sure that the system is always in good condition as well as to compare the performances of different techniques. By using this analysis, the determination for the future growth can be identified. From this research, it has been revealed that noise in the system indicates the performance of a system. The real values of R, X and B are 2.96 Ω, 32.40 Ω and 3.69 x 10^{-4} S while the values of estimated are 2.95 Ω, 32.42 Ω and 3.64 x 10^{-4} S respectively with noise 0.1. There are small differences between the real and new estimation values of R, X and B. The result shows the higher consistency involved in R, X and B value due to the approximate results between real and estimated values. While the real values of R, X and B are 2.96 Ω, 32.40 Ω and 3.69 x 10^{-4} S while the estimated values R, X and B are 2.67 Ω, 33.02 Ω and 2.84 x 10^{-4} S respectively with higher system noise of 50. Both of the calculated and estimated parameters are seen having less consistency and the results are slightly different due to the greater noise in the system.

The case study also shows the accuracy of resistance and inductance in the system more precise with the small value of noise which is 0.021 Ω and 0.021 mH respectively. Thus, it is shown that higher estimation accuracy will be achieved with the decreasing values of the noise. The table data also defines the system parameters of the simulink model with the greater value of noise which is 10. It shows the accuracy of resistance and inductance in the system is inaccurate with the greater value of error which is 0.28 Ω and 0.31 mH respectively. Thus, it is proved that the accuracy in the system will decrease with the increasing noise. The objective also has been achieved through the comparison and analysis the performance of Kalman Filter method in transmission line with Linear *Least Square* method and *Synchronous Phasor Measurement* method Kalman Filter.

Hence, it can be conclude that this research can be references for the parameter estimation field thus can help the engineers in the estimation of parameters for future growth even in a different area. In addition, with the different in accuracy according to the method used, this can be proven that Kalman Filter is one of the optimal method that can be used for estimation for real - time line parameter estimator. The reliability of this Kalman Filter method has been proven by using these two different places of parameter estimation which are RXB and RLC values. Thus, the proper parameters in the system can be estimated by using this technique.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Chapter overview

This chapter presents the conclusion and recommendation which have been made according to the results collected and discussed in the previous chapter. In this chapter, the conclusion will be discussed in the sub – chapter according to the objectives. This chapter summarize the significant outcomes from the research followed by the recommendation for the next improvement in the estimation of Kalman Filter based impedance parameter estimation for long transmission line.

5.2 Conclusion

In this chapter, some conclusions have been drawn based on the objective 1 and objective 2 of this research. The conclusions are summarize as below:

i. The development of Kalman Filter based estimation for RXB and RLC parameter for transmission line in Midland, England and distribution line in Universiti Malaysia Pahang has been done. The data from substation in Midland, England has been used as a main research to identify the estimation of impedance parameters and data from Universiti Malaysia Pahang (UMP) also has been carried out as a case study to prove the capability of Kalman Filter in estimation field. From this research, the value of noise affected the accuracy of RXB and RLC estimation in the system. The performance will decrease with the higher value of noises or disturbances in the system. The results of RXB and RLC estimation indicate the possibility for parameters estimation even in different places. It is important to consider that the values of RXB and RLC affected the determination of system efficiency in the transmission line.

ii. The comparison between Kalman Filter method with *Least Square* method and *Synchronous Phasor Measurement* method also has been done. From these two comparisons it shows that Kalman Filter is the best method that can be used in order to minimize errors in the system. Kalman Filter give a higher accuracy compared to the *Least Square* method and *Synchronous Phasor Measurement* method. It shows the accuracy of impedance parameters in the system is inaccurate with the greater value of errors. From these two results of parameter errors, it can be proven that Kalman Filter is a better method that can be used for estimation.

5.3 Recommendation

This research demonstrated the estimation of RXB and RLC values by using Kalman Filter method. According to the table and graph presented in the previous chapter, the value of noise affected the accuracy of RXB and RLC estimation in the system. The higher the value of noises or disturbances in the system, the performance will degrades. The results of RXB and RLC estimation indicate the possibility for parameter estimation even in different places. This research could be extended in some ways by the recommendation as follows :

i. From the finding, Kalman Filter method is better than Linear Least Square method. To conduct the comparison more thoroughly, larger simulation, real – world testing and further research should be conducted to confirm whether the Kalman Filter method can be effective for various three phase transmission line systems.

ii. Optimization method should be included in the next research in order to increase the classification accuracy rate in the estimation of impedance parameters.

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