THREE PHASE STATE ESTIMATION TECHNIQUES FOR NETWORK VOLTAGE UNBALANCE ASSESSMENT

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DEDICATION

To my parents for earning an honest living and for supporting and encouraging me to believe in myself. I dedicate this thesis to my family for nursing me with affections and love and their dedicated partnership for success in my life.

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ABSTRACT

Voltage unbalance is an important aspect of power quality. Unbalance can damage power equipment in a power system network, affect the operation of sensitive customer equipment and increase losses. Conventional Power system state estimation (PSSE) which assumes the network to be fully balanced does not capture the information related network voltage unbalance. Although, the single line representation of the network is good enough for most of the cases when it comes to transmission level, there can be certain locations in the power system, especially in the distribution network, which are prone to high voltage unbalance (VU) levels over which network operators wish to have full three-phase details in real time. To address this issue, completely switching into three phase model of the network which will add a significant computational burden, is not a feasible solution at all.

As a feasible remedy, this thesis introduces a novel methodology for voltage unbalance state estimation extending the conventional state estimation which can be selectively applied only for the locations of interest to capture the information related to network voltage unbalance, with minimum additional computational effort. The proposed three phase estate estimation make use of Singular Value Decomposition method to work out the estimation of three phase voltages and hence the complex voltage unbalance factor (VUF) at the locations of interest.

Proposed methodology is verified using IEEE 4 bus and 14 bus test networks simulating them using a three phase unbalanced power flow program written in MATLAB environment.

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LIST OF ABBREVIATIONS

Abbreviation	Description
VU	Voltage Unbalance
SE	State Estimation
SVD	Singular value decomposition
DSSE	Distribution System State Estimation
VUSE	Voltage Unbalance State Estimation

CHAPTER 1

1 INTRODUCTION

1.1 Motivation of Thesis

Presence of excessive levels of voltage unbalance stands as a power quality problem which has far reaching consequences for both customers and network operators. It is commonly encountered power quality disturbance which has been a concern at a distribution level. Even with small levels of voltage unbalance, customer and utility equipment can be damaged, degraded or mal-operated. Voltage unbalance is of primary concern to three phase rotating machines; especially adverse performance by induction motors where additional heat is produced in the windings, reducing the efficiency and thus leading to machine de-rating. Further, three phase power converters can draw unbalanced currents and generate non-characteristic harmonics creating additional power losses in the entire power system when supplied by unbalanced voltages. Basically in electric power systems VU is primarily caused by asymmetrical distribution of loads and untransposed transmission lines. Thus it is difficult to mitigate network VU completely.

The common practice is to manage the network VU levels to stipulated limits in order to meet the electromagnetic compatibility levels of the entire system.

The IEC compatibility standards (IEC 61000-3-13 [2] and IEC 61000-3- [3]) provide 2% compatibility level for VU in medium voltage (MV) and low voltage (LV) power systems allowing an excursion of up to 3% in some areas where predominantly single-phase loads are connected.

Further, a complexity in modern power system which comprises unusual types of loads and distributed generation resources at the distribution level has significantly increased the natural unbalance issues. Mitigation of VU is an important aspect in the management of network voltage unbalance where the resultant VU levels to be maintained by utilizing the maximum voltage unbalance absorption capacity.

In this regard, accurate assessment of network voltage unbalance plays a vital role in the management of VU. However, deterministic approaches require monitoring the entire power system, which is infeasible due to the cost associated with the monitoring points. Hence, there are limitations on the number of monitoring points a utility can afford to place on power systems. A cost effective solution can be provided by monitoring the system at a limited number of busbars and estimating the levels at unmonitored busbars. This forms the basis of Power Quality State Estimation (PQSE), which is the process of estimating the system unknown states from measured quantities.

State estimation methodologies are originally used for fundamental frequency state estimation work. However, the concept has been extended to PQ such as harmonics, transients, and voltage sags, with most of the focus on harmonics . PQSE is used to locate problem areas of the system by monitoring PQ levels at limited number of busbars and estimating the levels at unmonitored busbars. Therefore, PQSE is not one particular type of analysis but covers many different types in power quality area. Despite the different formulation and quantities they use, the common feature is that they are applying state estimation techniques to power quality problems. So far three phase Voltage unbalance state estimation is novelty area. In this study state estimation methodology is proposed to estimate the voltage in all the nodes and level of VU is calculated.

1.2 The Aim of This Project

The aim of this project is to extend current power quality state estimation (PQSE) concepts to VU emission assessment, by implementing a state estimation technique utilising a set of measurements to estimate the system states at unmonitored busbars in interconnected networks with constant impedance loads. A power system is represented as an equivalent mathematical model aiming at a close-to-realistic agreement with the true values of the system.

Therefore, by studying the response of the modelled network, the status of the real network can be approximately estimated. With limited input data and available analytical tools, the simulated output is expected to be sufficient and accurate.

The proposed voltage unbalance state estimation (VUSE) algorithm is able to accurately estimate the VU levels at unmeasured busbars in networks with unbalanced constant impedance loads. Estimation method used the singular value decomposition (SVD). However, the number of measurements must equal to the number of states when using Least Square LS method, while SVD is able to estimate states from available measurements with minimal percent error.

1.3 Approaches and Methodology

The development of a new algorithm for Voltage Unbalance State Estimation based on Singular Value Decomposition method has been used in this thesis. Firstly, theoretical formulation was formed for three bus system and extended to IEEE 14 test bus system. Using this approach three phase voltages are estimated in busbars.

The phase voltages are manipulated to obtain positive and negative sequence voltages for each busbar. Moreover, the VU levels are calculated for each busbar using the sequence voltages. A mathematical model relating the phase voltages and the phase impedances of the three-bus system is found using circuit analysis techniques. The resulting sets of equations relate the measurements to the states are solved using SVD estimations.

This method is extended to establish the Voltage unbalance state estimation (VUSE) formulations for the standard IEEE 14 test bus network and methodology is validated. Furthermore, the general Voltage Unbalance State Estimation formulation relating the phase voltage measurements and states, and the phase impedances of an interconnected network of any size is found, providing that the network topology is known. Measurements at some busbars are combined with Voltage unbalance state estimation code written in MATLAB to estimate the VU levels for the remaining busbars. The result is then validated against the values obtained from simulations.

A three phase unbalanced load flow program written in MATLAB was used to simulate the networks /test systems under study in order to fulfil the measurement requirement and subsequently, SVD techniques were applied.

1.4 Thesis Outline

Chapter 2 presents the detailed literature review including quantification of voltage unbalance, VU Causes and mitigation, as well as PQSE techniques.

Chapter 3 covers the development of theoretical formulations of the Voltage Unbalance State Estimation problem for constant impedance loads, and then the algorithms used to solve it.

Chapter 4 presents the analysis of the VUSE for IEEE 4 & IEEE 14 bus system under various types of measurement points. The estimation outcomes from MATLAB SVD are compared to the Load flow.

Chapter 5 concludes the thesis, summarizing the key outcomes from the estimation method and discuss the possible future work in VUSE that will complement this project.

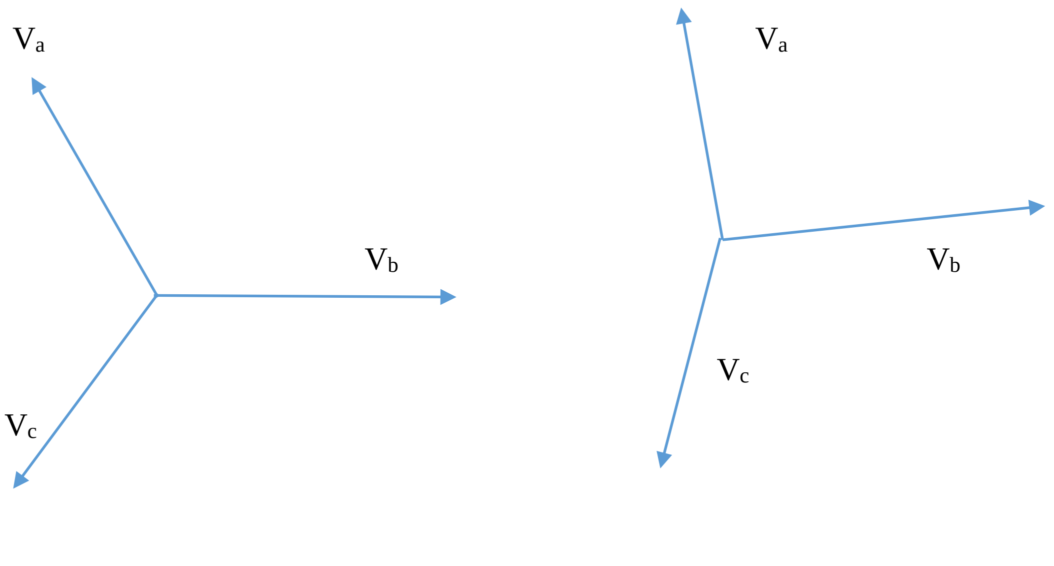
CHAPTER 2

2 LITERATURE REVIEW

2.1 General Overview of Voltage Unbalance (VU)

In three phase power systems, the generated voltages are sinusoidal and equal in magnitude, with the individual phases 120 apart. However, due to several reasons, the resulting three phase voltages at the distribution end and the point of utilization are unbalanced and not in equal magnitudes and/or phase separations. The nature of the voltage unbalance includes unequal voltage magnitudes at the fundamental system frequency and unequal fundamental phase angle separations.

Thus, Voltage unbalance is described as a condition in multiphase electric power systems in which the magnitudes of the fundamental phase voltages are not equal and/or the associated phase angle separations are different from the prescribed electrical phase angle.



(a) (b)

Figure. 2.1 Examples of balanced and unbalanced three-phase voltages. (a) Balanced three-phase voltages; (b) Unbalanced three-phase voltages

2.2 Quantification of Voltage Unbalance

The level of VU can be specified using a number of definitions [6, 7]. The widely used concept originates from the theory of symmetrical components which mathematically decomposes a three-phase unbalanced system into three balanced sub-systems known as positive, negative and zero sequence systems. Accordingly, VU can exist in two forms in a three-phase power system zero sequence and negative sequence unbalance. The presence of zero sequence unbalance is a concern only when there is a path for the flow of zero sequence currents, especially when the coupling transformer allows zero sequence currents to flow from higher voltage to lower voltage systems and vice-versa [8]. It is generally noted that the zero sequence unbalance can be controlled through system design and maintenance [1].

Conversely, negative sequence unbalance is relatively significant and is of concern compared to zero sequence unbalance as negative sequence current can flow through all power system components similar to positive sequence currents. Thus, the common practice is to pay attention to negative sequence unbalance in power systems.

The IEC Technical Report IEC/TR 61000-3-13:2008 [1] quantifies negative sequence unbalance by evaluating the negative sequence voltage unbalance factor (VUF) as the magnitude of the ratio of the fundamental negative sequence voltage (U_2) to positive sequence voltage (U_1) components as given in (2.1)

$$VUF = \left|\frac{U_2}{U_1}\right| \tag{2.1}$$

Mostly accepted by standards and international working groups [8] including EN50160, the Voltage Unbalance Factor (VUF), the ratio of negative sequence voltage (V_2) and positive sequence voltage (V_1), is the most widely used measure of unbalance. This factor expresses the proportion of negative sequence power flow to the normal working condition. Zero sequence power flow has a much smaller effect than negative sequence power flow, reflected by its absence in this factor (2.1).

NEMA Definition

The voltage unbalance percentage (VUP) at the terminal of a machine as given by the National Electrical Manufacturer Association Motor and Generator Standard (NEMA MGI) used in most studies is [K.S. Sandhu and Vineet Chaudhary 2008, P.Pillay and M.Manyage 2001]:

$$VUF(\%) = \frac{\text{max voltage deviation from average line voltage}}{\text{average line voltage}} \text{ X } 100 \ \ \% \qquad (2.2)$$

LVUR enhances the significance of average value, and takes the maximum deviation into account. By ignoring the behaviour of the other two voltages, it theoretically cannot result in high accuracy. However, LVUR is reported to have the ability to achieve close results with “true value” of voltage unbalance VUF in realistic networks

IEEE Definition

The IEEE definition [2] of voltage unbalance, also known as the phase voltage unbalance rate (PVUR), is given by

$$VUF(\%) = \frac{\text{max voltage deviation from the avg phase voltage}}{\text{avg phase voltage}} \text{ x } 100 \qquad (2.3)$$

The IEEE uses the same definition of voltage unbalance as NEMA, the only difference being that the IEEE uses phase voltages rather than line-to-line voltages. Here again, phase angle information is lost since only magnitudes are considered.
In this thesis definition of voltage unbalance is defined as the ratio of the negative sequence voltage component to the positive sequence voltage component.

Practical Approximation for VUF

IEC/TR 61000-3-13 [2] extends a practical algebraic approximation from IEC 61000- 4-30 for VUFs, shown in (2.4) and (2.5). This approximation employs only line magnitude values. It is reported to have a good agreement with the VUF value.

$$\text{VUF}(\%) = \sqrt{\frac{1-\sqrt{3-6\epsilon}}{1-\sqrt{3+6\epsilon}}} \ \text{X}\ 100 \tag{2.4}$$

$$\epsilon = \frac{|V|_{ab}^4 + |V|_{bc}^4 + |V|_{ca}^4}{\left(|V|_{ab}^2 + |V|_{bc}^2 + |V|_{ca}^2\right)^2} \tag{2.5}$$

Where V_{ab}, V_{bc} and V_{ca} are fundamental line-to-line RMS voltages.

2.3 Sources of Voltage Unbalance and Effects

Uneven Distribution of customer loads is a major cause of voltage unbalance which can be continuously changing across a three-phase power system due to the diverse nature of the power system. Uneven distribution of single-phase and two-phase loads4 and asymmetrical three-phase loads can cause unbalanced currents which can lead to voltage unbalance, even if the line impedances are symmetrical. On the other hand, a perfectly balanced three-phase voltage source supplying a perfectly symmetrical load through an untransposed line can also lead to unbalanced voltages at the load terminals due to the unequal mutual impedances resulting from the asymmetrical electromagnetic coupling between the conductors of untransposed/partially transposed overhead lines [19, 20, 21].

Due to the symmetrical construction and operation, central generation does not introduce any unbalance into the power system. Because the loads are distributed among three phases according to a previous construction plan, the changes in demand are unpredictable and there can hardly be equilibrium among the three phases internally as there is always the probability of connecting unbalanced loads, the balanced condition of the whole system is very difficult to guarantee. Due to unbalance, it will cause negative sequence power flow and over voltage in some of the phases. Which leads to the thermal aging and furthermore reduction in equipment life time. Unexpected negative sequence power flow reduces the efficiency of the generators and motors. Negative impacts on equipment construction and utilization, the damage caused by unbalance will finally result in additional economic costs.

Three-phase induction machine creates an internal magnetic field and produces a positive torque as a result. The magnetic field and torque are proportional to the positive sequence voltage of the induction machine. Once exposed to unbalance, the existence of negative sequence component generates an inverse rotating magnetic field, which changes the circular trajectory into elliptical [3] and produces an inverse torque, forcing the machine to decelerate. Fig. 2.1 shows the sequence torques (T) against the slip (s). Positive sequence torque (T1) is known as the normal working condition torque, and negative sequence torque (T2) acts against the rotation. In other words, under unbalanced conditions, the negative torque is added to the working torque so that the total torque is reduced compared to the initial working torque. With the presence of the negative sequence torque, the machine cannot rotate at full torque and full speed. At the same time, because of the induced torque components at twice the system frequency, the pulsating torques may appear and the shaft bearings are exposed to higher mechanical stress. Because of the negative sequence impedance, the negative sequence component causes large negative sequence current. This in turn could amplify the input unbalance by 6-10 times. As a result, both the stator and rotor of the machine experience are overheating and loss as well as fast thermal ageing. [4]

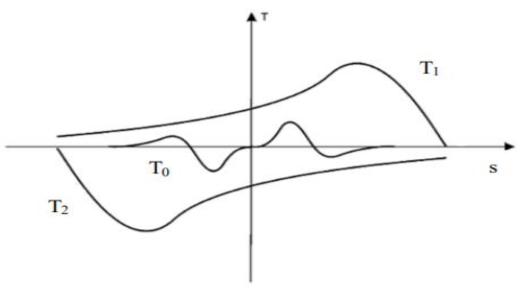


Figure2.2 Sequence Component Torques of Induction Machine [4]

Related to transformers, two effects can be discovered. First, depending on the transformer winding connection type, zero sequence power flow may become possible if zero sequence current exists. Although it does not cause a large problem for the network, it may circulate within the delta winding and contributes to the increment of winding temperature, which leads to additional loss and damage. Secondly, negative sequence flux and current can cause parasitic due to same flowing path as positive power flow.

In power electronic devices; the uncontrolled Diode rectifier front ends lead to the irregular harmonics and resonance power in electronics interfaces, e.g. the ASDs, are sensitive to the input current. The ASDs are typically composed of diode rectifier front-ends [5] or Pulse Width Modulated (PMW) rectifier front-ends [5] [6]. When a PMW rectifier is exposed to unbalanced input voltage, the current distortion is increased as well as the reactive power and double frequency voltage ripple appears in the dc-link capacitor [5][6]. The excessive currents appear in one or two phases, enabling the aggravation of the unbalance phenomenon and the potential triggering of the protection [5].

General problem due to the unbalanced sequence the negative sequence current induced coupling affects all the apparent powers and power factors along the line, the common damage to all applications is overheating. Due to that reason, machine efficiency is immediately reduced and degration may need to be applied; furthermore, it raises economic cost issues. Because of heating lifetime is decreased. Additionally, extra noise and vibration are likely to occur during unbalance [45].

2.4 Mitigation of Voltage Unbalance

Mainly VU corresponding to the main cause, the most basic mitigation method for unbalance is to rearrange the loads to an evenly distributed condition among three phases [8]. By changing the system configuration through manual and automatic feeder switching operations to transfer loads among circuits will facilitate to balance of electrical distribution systems [9]. These phase reconfiguration techniques use load estimation algorithms to optimise feeder switching, but they cannot dynamically balance the system load since they are performed in a discrete manner. Theoretically, electromagnetic coupling effects can be neglect by the complete transposition of overhead lines and/or the use of proper tower arrangements, VU which arise due to line asymmetries nullified [39]. However, these ideal conditions can rarely be achieved in practice due to economic constraints and practical difficulties. Thus, the implementation of more appropriate design options in terms of tower configuration [20] and phase positioning/swapping at transposition points of multi-circuit lines [7] [10] are recommended.

When excessive VU levels are unavoidable, special balancing equipment can be installed at the utility and/or plant level [11] [12] [13]. Power electronic based static compensators are set to balance the load current by the injection or absorption of reactive power to or from the supply network. Some modern var compensators facilitate control algorithms for dynamically correcting voltage unbalance. The use of special power electronic circuits effectively controls the connected source of unbalance as power electronics respond swiftly to compensate for the changes in each phase when exposed to an unbalanced load or generation [15]. The shunt connected static compensators, such as passive static VAR compensators [14], static synchronous compensators [13] and distribution static compensators [79], injecting or absorbing reactive power to or from the power system, help regulating the voltage unbalance in the network. Devices such as unified power quality conditioners (UPQC) and hybrid active and passive filters [48], which are capable of compensating various power quality disturbances simultaneously, can be employed to mitigate unbalance as well.

2.5 Voltage Unbalance Emission Assesement

IEC technical report 61000-3-13 [3], Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems “[1] from the IEC 61000-3 series provides guidance on principles which can be used as the basis for determining the requirements for the connection of unbalanced installations (i.e. three-phase installations causing voltage unbalance) to MV, HV and

EHV public power systems. Assumptions have been taken regarding unbalance emission assessment.

- Pre-existing background will not be influenced by connection of the installation unbalance.
- POE will not influence the unbalanced current.

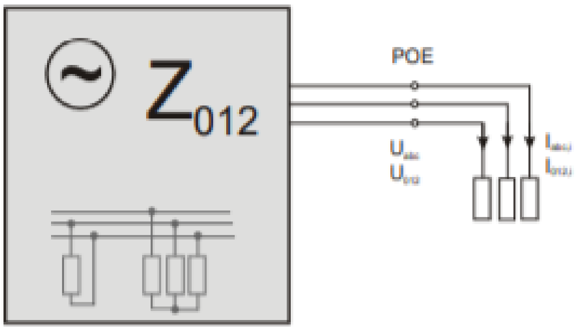


Figure. 2.3: Network with pre-existing unbalance (existing unbalanced loads) and unbalance level at the point of evaluation

According to standards, unbalance is expressed by the negative sequence voltage U_2 respectively by the ratio of U_2 and U_1. Hence, the negative sequence voltage U_2 at POE can be written as shown in (4), consisting – besides the pre-existing unbalance - of three parts:

$$U_{2}= U_{2,oc} - (Z_{21} * I_{1,i} + Z_{22} I_{2,i} + Z_{20} I_{0,i}) \qquad (2.8)$$

- The product of the coupling impedance Z_{21} respectively Z_{12} (between positive and negative sequence system) and the currents of the positive sequence system $I_{1,i}$ can be of significance as the positive sequence current is usually large although the coupling impedance Z_{21} is relatively small.
- The product of the negative impedance Z_{22} (often denoted simply as Z_2) and the current $I_{2,i}$ of the installation can be of significance.
- The product of the coupling impedance Z_{20} (between zero sequence system and negative sequence system) and the zero-currents $I_{0,i}$ can be neglected due to the fact that the coupling impedance Z_{20} and the zero sequence current $I_{0,i}$ are usually very small.

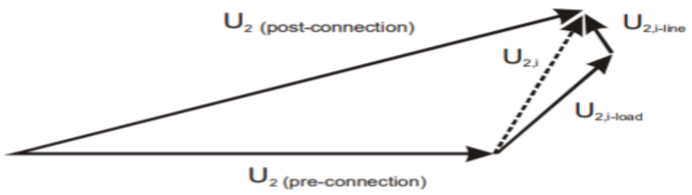


Figure. 2.4: Unbalance level and unbalance emission at the POE

2.6 Power Quality State Estimation

The power system network is increasingly becoming more and more complex with the increase in energy demand. A power quality problem is any unexpected deviations in magnitude, angle or frequency in voltage or current, causing failure or miss operation of any power system component or customer device [1][2]. Power quality describes the extent at which voltage or current waveform deviates from the ideal three-phase sinusoidal wave. The power quality phenomena include short term interruptions and long term disturbances. Power quality also represents the compatibility between the power system supply and the connected equipment at the point of connection. Asset may suffer excessive heating, accelerated thermal ageing and reduced efficiency if the power is supplied with poor quality. Cause of this it will lead to the additional cost for the both end user and the network operator. So the problem has to be concern in two aspects one is how the power affects the load and how the load affects the power system in return from the customer's perspective, Power quality is to supply steady state high performance voltage that can continually feed applications. Otherwise, may cause a loss of temporary work, process delay, equipment damage and possible penalties due to late delivery and poor power quality.

When we categories the problems in customer side and utility side voltage sag surges, short term outages transients and voltage unbalance harmonics etc. In customer side, utility side voltage stability,harmonices,voltage sag transient ,phase shift and so on .Considering these issues stable power quality allows electrical power system to function normally and ensure the lifetime of all equipment along the line [2].

Equation (8) represents the broad formula of the state estimation problem. In which, z is a vector of known measurements; x is a vector of unknown state variables, H is a function relating measurements to state variables, and is the measurements errors vector.

$$z = \mathbf{H}_{(x)} + \text{€} \tag{2.9}$$

The three mostly used methods or criteria in state estimation are listed and described as follow:

1. Maximum Likelihood: This method is used to maximize the probability that the estimated value for the state variable is close to the actual value.
2. Weighted Least Squares (WLS): This method is the most popular method in the industry. Its main objective is to minimize the sum of the squares of the difference between the estimated and the actual value of the state variable, which is also known as the error.
3. Minimum Variance: The minimum variance is similar to the WLS, but it minimizes the expected value of the sum of the errors as described in the WLS method.

2.7 Weighted Least Squares Method (WLS)

Weighted Least Square (WLS) method is one of the most commonly used methods for power systems state estimators tool. This report explains how state estimation methods aim to predict the closest possible approximation for the state variable. The maximum likelihood principle is to increase the probability of getting close to the "true" value; however, another approach is to minimize the difference between the approximated value and the actual state variable value. This is exactly what WLS method does. Its main objective is to minimize the squares of the measurements errors. This section describes the WLS algorithm, formation of the measurement function and the Jacobian matrix, and provides an example to show how WLS method can be applied to a network.

Let $z=\begin{bmatrix} z_1 \\ \vdots \\ . \\ z_m \end{bmatrix}$ $h_{(x)}=\begin{bmatrix} h_1 \\ \vdots \\ . \\ h_m \end{bmatrix}$ $R=\begin{bmatrix} \epsilon_1^2 & & \\ & \ddots & \\ & & \epsilon_m^2 \end{bmatrix}$

$$H^T{}_{(x)}R^{-1}[z - h_{(x)}] = 0$$

Can solve iteratively. If each hi is a linear function of x, i.e., $h(x) = H_x$,

Then $H^T R^{-1} z - H^T R^{-1}H_x = 0$ (2.10)

Closed-form solution exists

$$x\hat{} = H^T R^{-1}H^{-1} H^T R^{-1}z \quad (2.11)$$

If the number of state variables is less than or equal to the number of equations, the system is called over-determined or completely determined. However, if the number of state variable is greater than the number of equations, the system is called under-determined. A system is considered fully observable if measurements could be used to determine the complete system state. However, if only some of the state variables could be determined the system is considered partially observable.

A conventional solution technique to solve fully observable systems is the" normal equation method", which is usually used for fundamental frequency state estimation. Initially PQSE also used the normal equation method. However, a separate observability analysis process is carried out first to determine the solvability of the measurement equation [14]. A different method for solving the measurement equation is proposed by [15] using the Singular Value Decomposition (SVD) method, which eliminates the need to use the observability analysis function. This method is also able to give a reliable solution for partially observable systems, which was not possible using the normal equation approach. However, SVD computation is more complex than estimation using the normal equation.

A cost effective solution can be provided by monitoring the system at a limited number of busbars and estimating the levels at unmonitored busbars. This forms the basis of PQSE, which is the process of estimating the system unknown states from measured quantities, which cause deterministic methodology inefficient.

2.8 Singular Value Decomposition

The SVD method is usually used for solving matrices that are either singular or close to singular. Under this situation the normal equation approach fails to provide matrix inverse and hence reliable results. However, compared to the normal equation approach, a computational requirement to perform SVD is much higher. The SVD method is based on the linear algebra theorem saying that any M×N matrix H can be rewritten as.

$$[H]_{mxn} = \begin{pmatrix} U_{1,1} & \cdots & U_{1,m} \\ \vdots & \ddots & \vdots \\ U_{42,1} & \cdots & U_{m,m} \end{pmatrix} . \begin{pmatrix} S_1 & & \\ & \ddots & \\ & & S_n \end{pmatrix} . \begin{pmatrix} V_{1,1} & \cdots & V_{1,n} \\ \vdots & \ddots & \vdots \\ V_{m,1} & \cdots & V_{n,n} \end{pmatrix}^T$$

$$[H]_{mxn} = U_{m,m} . S_{nxn} . V_{n,n}{}^T \qquad (2.12)$$

where U (m×m) and V^T (n×n) are orthogonal matrices and S (m×n) is a diagonal matrix with the entries of singular values of H. These factored forms can be calculated through eigenvalue analysis. SS^T is an eigenvalue diagonal matrix. [U] is the eigenvector matrix of HH^T and its columns whose same numbered elements of singular values which are non-zero are an orthonormal set of basis vectors that span the range of matrix H. [V] is the eigenvector matrix of $H^T H$ and its columns whose same numbered elements of singular values which are zero are an orthonormal set of basis vectors that span the null space of matrix H

2.9 Observability Analysis

A normal equation approach that prior Observability Analysis (OA) is performed to ensure the system observability. It can be applied only when the system is fully observable and hence an inverse of matrix H exists. However, SVD is able to give reliable answers for some state variables even when the system is partially observable. Moreover, inspection of the singular values and component matrices also gives important information on observability.

This can simply be done through MATLAB command [U, S, V] = svd (H) which returns three factored matrices U, S, V representing [H]. [S] and [V] will be in the form of

$$S_{m\times n} = \begin{array}{c} 1^{St} \\ \vdots \\ i^{th} \\ \vdots \\ m^{th} \\ \vdots \\ \\ \vdots \\ n^{th} \\ \\ \end{array} \begin{pmatrix} s_1 & & & & & & \\ & \ddots & & & & & \\ & & s_i & & & 0 & \\ & & & \ddots & & & \\ & & & & s_m & & \\ & & & & & \underbrace{s_{m+1,n-2}}_{0} & & \\ & & & & & & \underbrace{s_{m+2,n-1}}_{0} & \\ & & 0 & & & & & \underbrace{s_{m+3,n}}_{0} \end{pmatrix}$$

$$V_{n\times n} = \begin{array}{c} \\ 1^{St} \\ \vdots \\ i^{th} \\ \vdots \\ m^{th} \\ \vdots \\ \vdots \\ n^{th} \end{array} \begin{pmatrix} 1 & & & \cdots & & n-2 & n-1 & n \\ v_{1,1} & \cdots & & & & & & \\ \vdots & \ddots & \vdots & & \vdots & \vdots & \vdots & \vdots \\ v_{i,1} & \cdots & v_{i,i} & \cdots & v_{i,m} & v_{i,n-2} & v_{i,n-1} & v_{i,n} \\ \vdots & & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ & & & & v_{m,m} & & & \\ & & & & & v_{m+1,n-2} & & \\ & & & & & & v_{m+2,n-1} & \\ & & & & & & & v_{m+3,n} \end{pmatrix}$$

The singular values of matrix [S] are sorted in ascending order and for the elementsn− 2, n − 1 and n are zero. In this case, inspecting the same numbered columns in [V] defines a set of basis null space vectors as well as the system observability. For example, i th state variable is observable if and only if all the entries of [$V_{i,n-2}$ $V_{i,n-1}$ $V_{i,n}$] are zero.

2.10 History of Power Systems State Estimation

First two decades of power system state estimation from1969 until 1989, talking about the discoveries and improvements done towards the implementation of state estimation. Fred Schweppe, however, was the person who introduced the Weighted Least Square (WLS) method for power system state estimation back in 1969 [18]. Several methods such as decoupled WLS, and the Least Absolute Value (LAV) methods were developed based on this concept. His original method is used until now in state estimation applications and dominating other technique

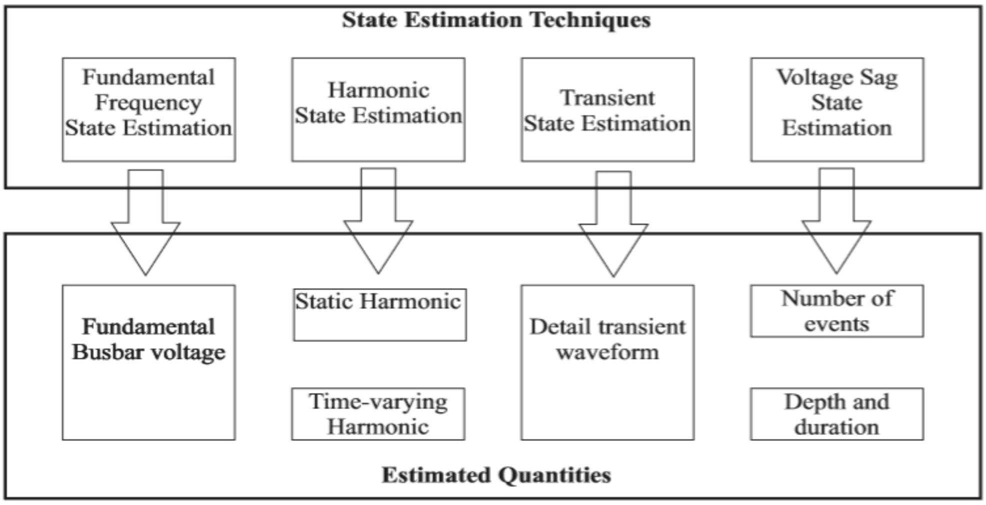


Figure 2.5State Estimation Techniques and estimated quantities

Harmonic State Estimation (HSE) techniques estimate the harmonic voltages and currents throughout the system from limited measured harmonic data [8-10]. This is the reverse of harmonic penetration which calculates the harmonic voltages and harmonic currents from knowledge of the harmonic sources and the system topology and system parameters. In HSE the harmonic source locations and magnitude are estimated, along with the harmonic voltages and currents, from a limited number of harmonic measurements. Due to the present cost of PQ monitors it is unlikely that the system is overdetermined which necessitates the use of Singular Value Decomposition (SVD) as it can solve under-determined systems rather than the traditional Normal equation approach. The SVD algorithm is robust and gives additional information, such as observability, however it is computational more demanding, which is not an issue if estimating a quasi-steady-state phenomenon like harmonics. A great deal of work has been done on HSE from different points of view such as finding the optimal number of the measurements and the best location for them [19], bad data analysis [20], varying harmonic levels with time [21], estimating the type of loads and hence which generate harmonics [21]. Implementation of HSE, based on a field- test data in Japan also has been presented in [22].

Voltage Sag State Estimation (VSSE) is generally considered in two main areas. The first area refers to the number of voltage sags arising at unmonitored busbars from the number (frequency) of sags/dips obtained at a limited number of monitored busbars, the second area refers to the use of estimation techniques to measure the sag/dip magnitude and duration at every point on a distribution feeder [16]. This can then be used to calculate power quality indices such as the system Average RMS Frequency Index (SARFIx) [23]. The next contribution in this area optimizes the number and location of the PQ monitors for observing a large transmission network in terms of voltage sags, and then deploys it for calculating voltage sag system indices [24]

TSE is a reverse function of transient simulation. Transient simulation is used to analyse the consequences of a disturbance on a power system voltage, currents, etc., TSE is exploited to identify the cause of transient disturbances. Therefore, TSE can be used potentially as a valuable tool for diagnostic purposes in power systems. Transients necessitate a time-domain solution for the system and hence a dynamic formulation to represent the system and its components. The two broad classes of methods used in the digital simulation of the differential equations representing continuous systems. They are, numerical solution of the differential equations via state-variable approach or converting to difference equations by use of a numerical integrator (i.e. Numerical Integrator Substitution (NIS) or otherwise known as Dommel's method [25]

2.11 Distribution System State Estimation (DSSE)

Traditional state estimation network is entirely balanced and calculated using single-phase models. Network is considered as fully observable [20] if the voltage magnitudes and angles at every bus are available for all operating conditions. However, the assessment of unbalance requires three-phase state estimation, because unbalance is between phases and the assessment focuses on the evaluation of the difference between phases. By using three-phase state estimation, the voltage and current vectors of all three phases are approachable, as demonstrated in [21]. Weighted Least Square method is applied similar to the single-phase state estimation [21], to the three-phase state estimation whereas phases and their correlations should covered through the state variable equations and Jacobian matrix. Unlike traditional state estimation which assumes enough measurements from monitors in the power system [21][22] Distribution Network State Estimation (DNSE) is designed for the situation in distribution networks where the measurements are less available due to the limited number of monitors. Due to a lack of operating data, DNSE is needed in order to provide full observability of the network aiming at real-time estimation. To achieve this goal, pseudo measurement [23] is employed to estimate the parameters in the unobservable area. In this way, the estimated values developed from historical data enable the full observability of the power system [24]. DNSE is usually executed under a balanced condition in which the network is again considered as single-phase but it can be extended to three phases. DNSE uses the same power flow equations with Newton-Raphson power flow method. The probabilistic three-phase load flow structure is developed in and detailed flow equations are discussed in [24]. The probabilistic nature of the methodology enables both real-time and long term studies of voltage variations in power systems.

CHAPTER 3

3 Theoretical Formulations of the Voltage Unbalance State Estimation

The proposed three-bus network in Figure 3.1 is the preliminary starting point for the VUSE problem. Assuming that the phase voltage is measured at one and current at one and three busbars, the proposed VUSE algorithms are used to estimate the voltage unbalance factor (VUF) at unmonitored busbars.

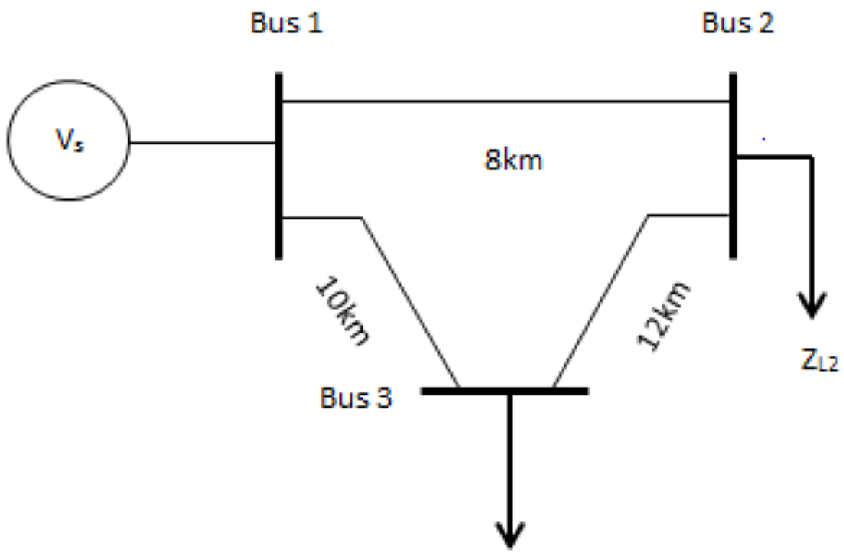


Figure 3.1: Three-Bus Interconnected Network.

Details of the 3 bus system is given in Appendix 1. Output obtained in different scenario tabulated.

3.1 Formulation of the VUSE Problem

The formulations presented in this section generate the equations relating the phase voltages and phase impedances of a three-bus system. The equations represent a mathematical modelling of the system and are solved using the proposed VUSE algorithms. These equations are then extended to an n-bus interconnected network of any size, providing that the topology of the network is known. Proposed method is validated with IEEE 14 standard bus.

$$([V_2] - [V_1]) * [y_{12}] - ([V_3] - [V_1]) * [y_{13}] = I_1 \quad (3.1)$$

$$([V_1] - [V_2]) * [y_{12}] - ([V_3] - [V_2]) * [y_{23}] = I_2 \quad (3.2)$$

$$([V_2] - [V_3]) * [y_{23}] - ([V_1] - [V_3]) * [y_{31}] = I_3 \quad (3.3)$$

The above equations are rearranged in order to make the matrix manipulation.

$$((y_{13} - (y_{12})) * [V_1] + (y_{12}) * [V_2] - (y_{12}) * [V_3] = I_1$$

$$(y_{12}) * [V_1] + ((y_{23} - (y_{12})) * [V_2] - (y_{23}) * [V_3] = I_2$$

$$-(y_{31}) * [V_1] + (y_{23}) * [V_2] + ((y_{31} - (y_{23})) * [V_3] = I_3$$

The general form of the phase current, phase voltage and phase admittance matrix for all nodes is given below.

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (3.4)$$

Assuming that the phase voltage is measured at one, current at one and 3 bus bars, rearranging the equation as below

$$\begin{bmatrix} V_1 \\ I_1 \\ I_3 \end{bmatrix} = \begin{bmatrix} I & 0 & 0 \\ Y_{11} & Y_{12} & Y_{13} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \quad (3.5)$$

Where I is identity matrix, Z_V , Z_i are voltage and injection current measurement sub vector, respectively, Y_M, Y_C are the node admittance matrix of measurement and calculated busbar voltage that related to Z_i,respectively, V_M, V_C are measurement and calculated(unmeasured) busbar voltage subvector.

$$\begin{bmatrix} Z_V \\ Z_i \end{bmatrix} = \begin{bmatrix} I & 0 \\ Y_M & Y_C \end{bmatrix} \begin{bmatrix} V_M \\ V_C \end{bmatrix} \quad (3.6)$$

Extract the coefficient of measured current from admittance matrix Partition measurement matrix according to whether measured (V_m)or calculated, by inspecting each element of admittance matrix a relationship (Partition measurement matrix according to whether measured (V_m)or calculated) between the admittance matrix and the measured and unmeasured vectors can be formed ((n*3)-2)

For a given measurement set and system topology, the basic circuit laws lead to the following measurement equation.

$$Z = H_x + r \qquad (3.7)$$

Where z and x are the vectors of measurements and state variables, respectively. H is the measurement matrix, and r is the measurement noise vector, which is assumed to be made of independent random variables with Gaussian distribution.

The SVD is a very powerful set of techniques for dealing with sets of equations or matrices that are either singular or else numerically very close to singular. In some cases, where Gaussian elimination and LU decomposition fail to provide satisfactory results, the SVD will diagnose precisely what the problem is. In some cases, the SVD will not only diagnose the problem, but it will also solve it, in the sense of giving a useful numerical answer. The SVD is also the method of choice for solving most linear least-squares problems.

The SVD method represents the matrix H (m*n) of Eq (7) as the product of three. When m is the number of measurement placement, and n is the number of state variable.

$$H=USV^T \qquad (3.8)$$

S is a diagonal matrix (n X n) with positive or zero elements, which are the singular values of H. Matrices U and VT are orthogonal matrices, U being a column orthogonal (mX/n) matrix and V^T is the transpose of a (nXn) orthogonal matrix. From Eqs. (8) and (7) the following expression of x is obtained.

$$X=VS^{-1}U^TZ \qquad (3.9)$$

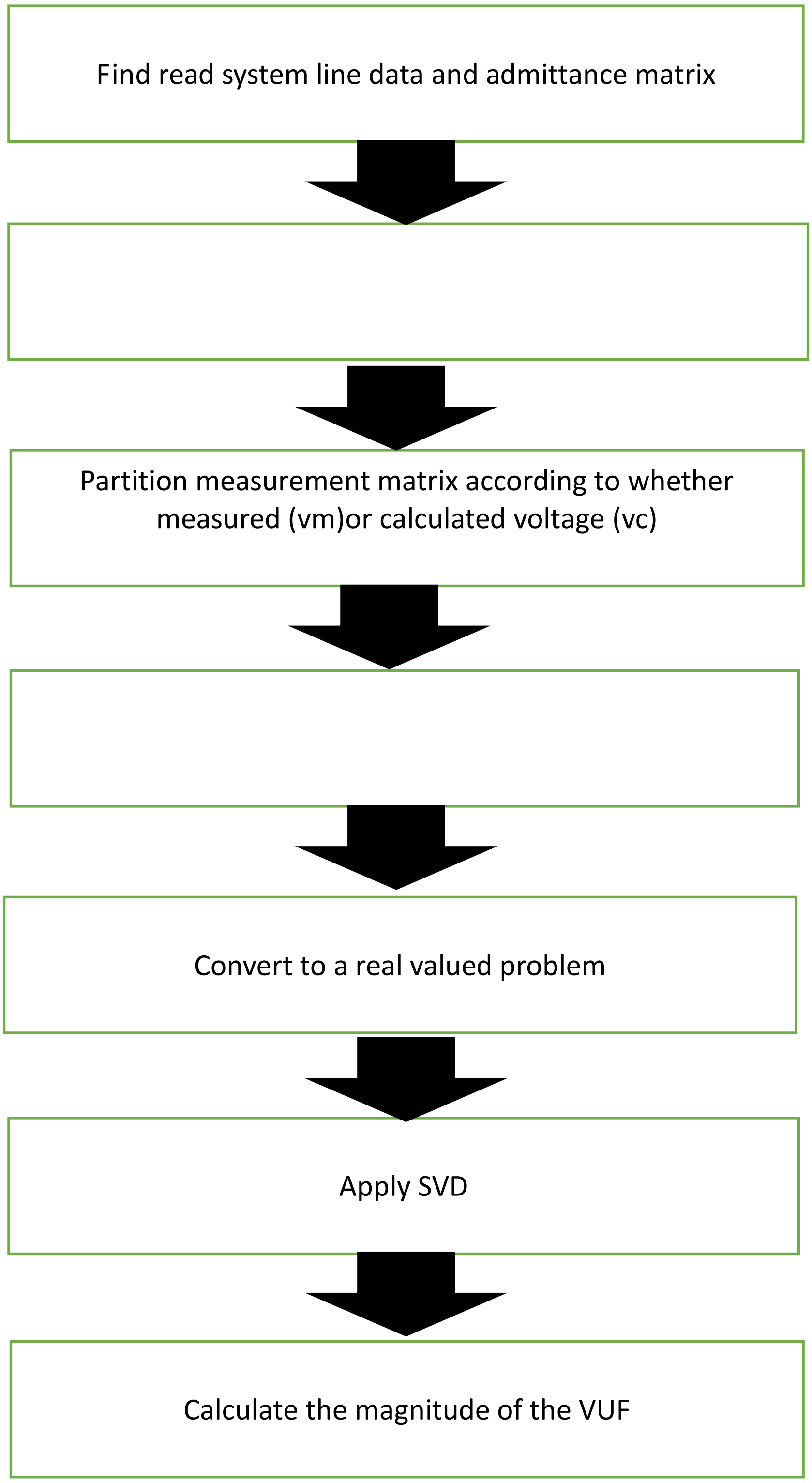


Figure 3.2 General algorithm of SVD state Estimation

The block diagram in Figure 3.2 outlines the general algorithm of SVD state estimation. MATLAB Code is developed respect to the algorithm used to approximate the VU states. Appendix A has the complete MATLAB code used to estimate the VUF at unmeasured busbars in IEEE 14 bus network with unbalanced loads using SVD.

The main function takes the input user defined data and calls the other functions for other operation. Finally give the error % as an output.

The phase voltage measurements injected current and the phase impedances for the transmission lines are specified at the start of the main function, phase voltage measurements are obtained from the load flow.

The line and load phase impedances are used to create the system impedance matrix. The diagonal elements in the impedance matrix are the loads impedances at different busbars, while the off-diagonal elements are the line impedances between different busbars.

The main function contents the 6 different cases and calls two sub function for estimation one is normal and real imaginary calculation, two different sub function to contain line parameters and is used to calculate the diagonal elements in the coefficients matrix, which relates the network.

Admittance matric will be re arranged according to measured current and voltage with identity matrix.

SVD estimations are used to calculate the states phase voltages in the main functions. Sequence voltage values then the VUF for each state. The VUF values are expressed in polar form, with the magnitude as a percent value.

As well system observability can be identified using SVD, which part of the network is unobservable island. Singular values in diagonal S matrix and null space vector matrix V which will identify the unobservable busbar.

CHAPTER 4

4 Application of Proposed Formulation for Standard Test System

4.1 IEEE 4 Bus System

The power simulation program with unbalanced load-flow code written in MATLAB will be used to set up test networks such as IEEE 4 bus system and to generate the data required for the state estimation. Details are given in Appendix 3

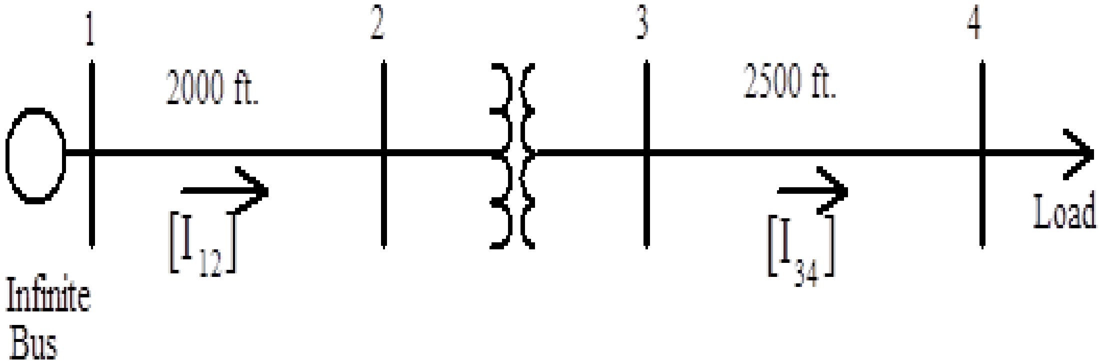


Figure .4.1 IEEE 4 bus test system

The proposed methodology was applied to the IEEE 4 bus test system shown in Figure .4.1 which is supplying constant power loads. Busbars 2 nd 3rd are in connected with the transformer. Three phase transformer data is shown below.

Table 4. 2 Transformer Details

Connection	kVA	kV_{LL}-high	kV_{LL}-low	R - %	X - %
Step-Down	6,000	12.47	4.16	1	6
Step-Up	6,000	12.47	24.9	1	6

Unobserved Island parameters are estimated using SVD. Estimated voltages are compared with Load flow data and error is calculated.

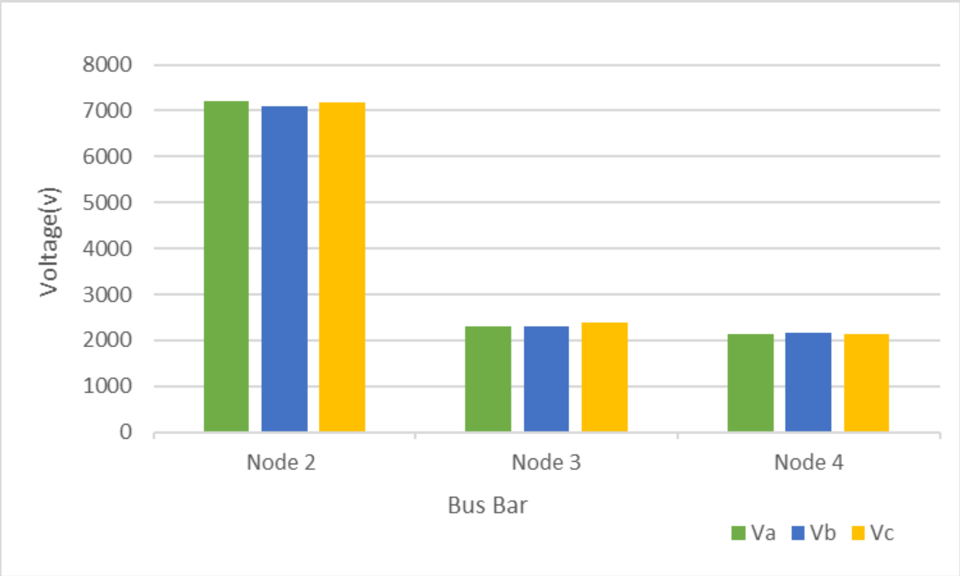


Figure 4.2 Estimated Voltages

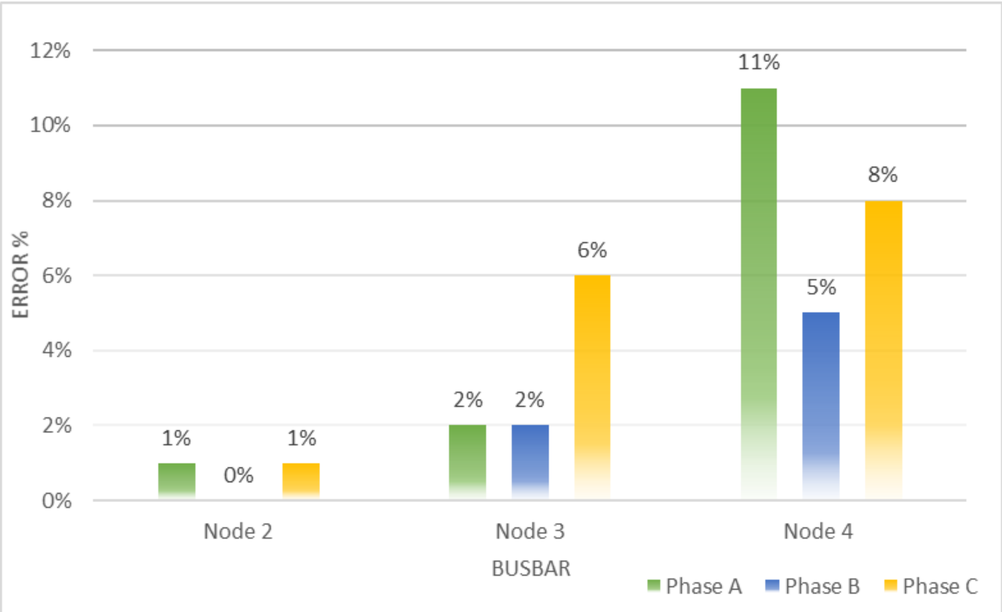


Figure 4.3 Estimated Voltages Error %

Table4.2: Estimated Voltages &Load flow Output

Nodes	Magnitude (V)		Error %
	Estimated	Load flow	
V3	2294	2248	2%
	2304	2269	2%
	2390	2256	6%
V4	2135	1918	11%
	2164	2061	5%
	2142	1981	8%
V2	7209	7107	1%
	7111	7104	0%
	7170	7121	1%

IEEE 4 bus system estimated voltages at un measured points graphically shown in fig 4.2 and obtained voltages compared with the out obtained through the IEEE 4 bus load flow data. Error % calculated tabulated in table 4.2.

4.2 IEEE 14 Bus System Analysis

The proposed methodology was applied to the IEEE 14 bus test system shown in Figure .4.5 which is supplying constant power loads. Busbars 1, 2, 3, 6 and 8 are considered to be balanced, voltage controlled busbars. All transmission lines are considered to be identical in construction, of different lengths and transposed. The 60 Hz, three wire test system was modelled as per the data given in [4] and [64]. The data of the IEEE 14 bus test system used in this study is given in Appendix 2.

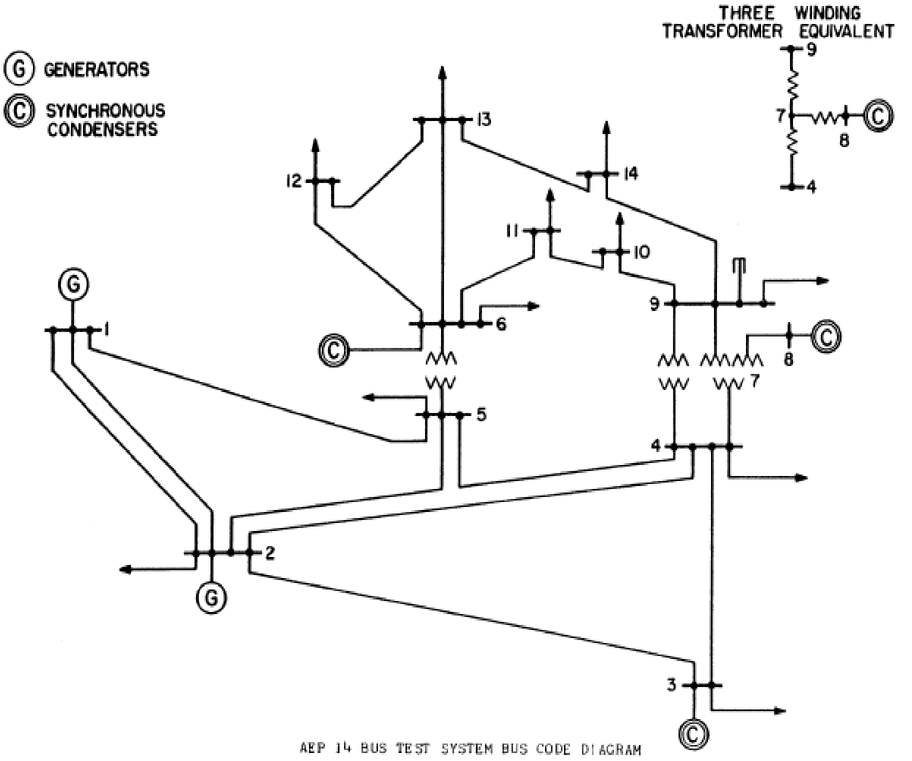


Figure 4.3: IEEE 14 standard bus system

The values of the phase voltage measurements vector and measured current vectors are obtained from the load flow MATLAB is then used to evaluate the states coefficients matrix and the measurements coefficients matrix. The measurements are combined with state and measured coefficient to solve for the unknown phase voltage states vector using singular value decomposition (SVD) methods. Furthermore, the estimated phase values are converted to sequence values to calculate the voltage unbalance factor (VUF) from MATLAB at the unmeasured busbars, which were then compared with the VUF acquired load flow outputs.

Table 4.3: Measurement placement & Performance of SVD

Case	**Bus voltages**	**Busbar injection current**	**Unobservable**	**Comments**
1	1,5,9,10,14	1,5,9,10,14	8,12	singularity
2	1,2,4,5,8,9,13,14	1,2,4,5,8,9,13,14	11	singularity
3	1,2,4,5,8,9,11,13	1,2,4,5,8,9,11,13	-	fine
4	1-5,9,10,12,14	1-5,9,10,12,14	8	singularity
5	3,4,6,7,9,14	1,3,5,6,10,13	8	singularity
6	4_10	1-3,10-,14	-	fine

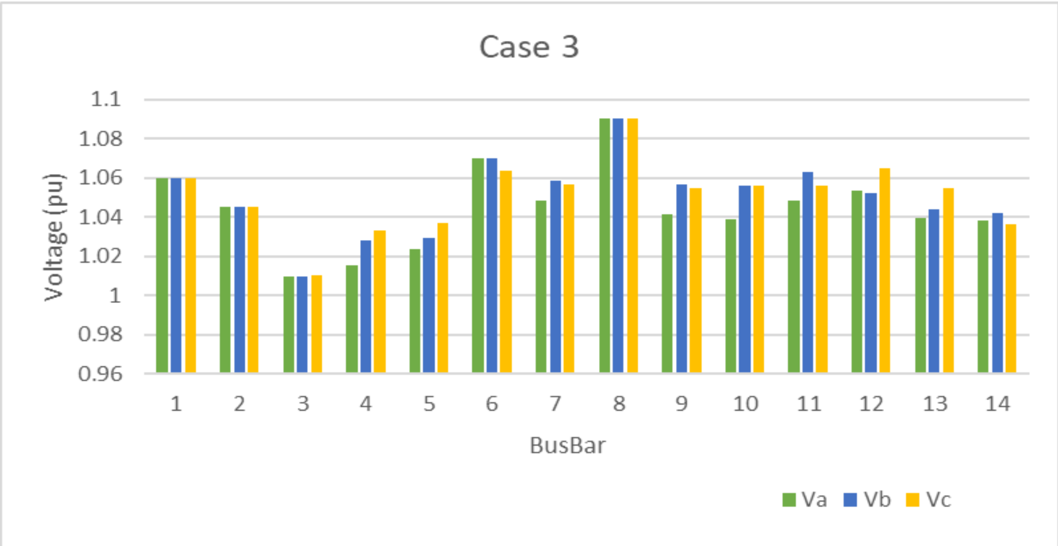


Figure 4.5 Estimated Voltage at busbar

The above table shows the measurement placement and performance of SVD approach in each case.

There are six cases where bus voltage and busbar injection currents are taken in different measurement points. From the approach it was able to observe bus 8,11 and 12 are unobservable island where singularity. On the study IEEE 14 bus test system it is found that the SVD approach can identify which part of the system is unobservable. Below table shows the all 14 busbar voltage of case one and three whereas voltage for all three faces are shown separately.

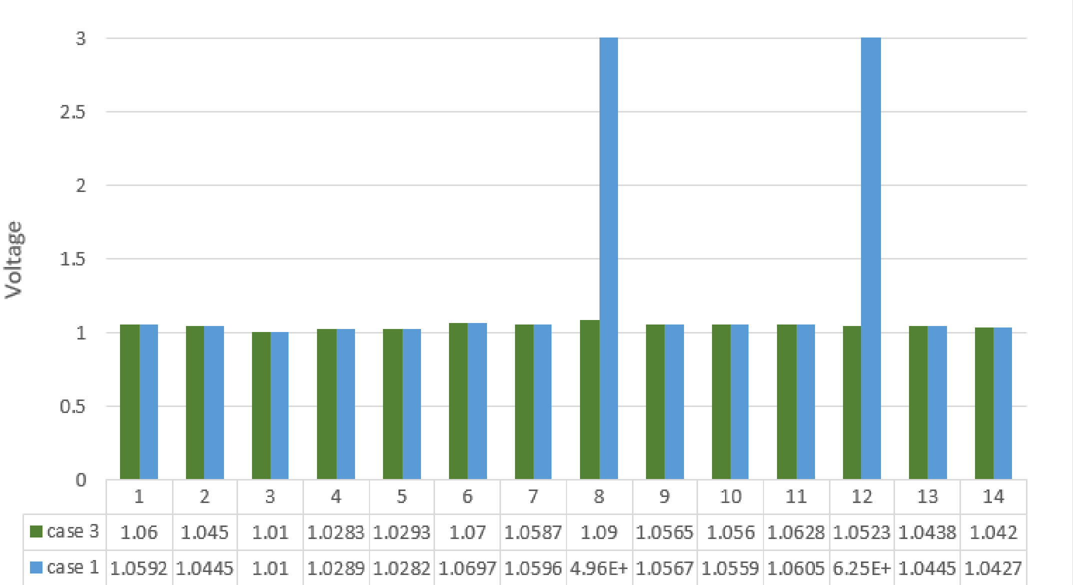


Figure 4.6 Estimated Phase A voltage in Case 1,3

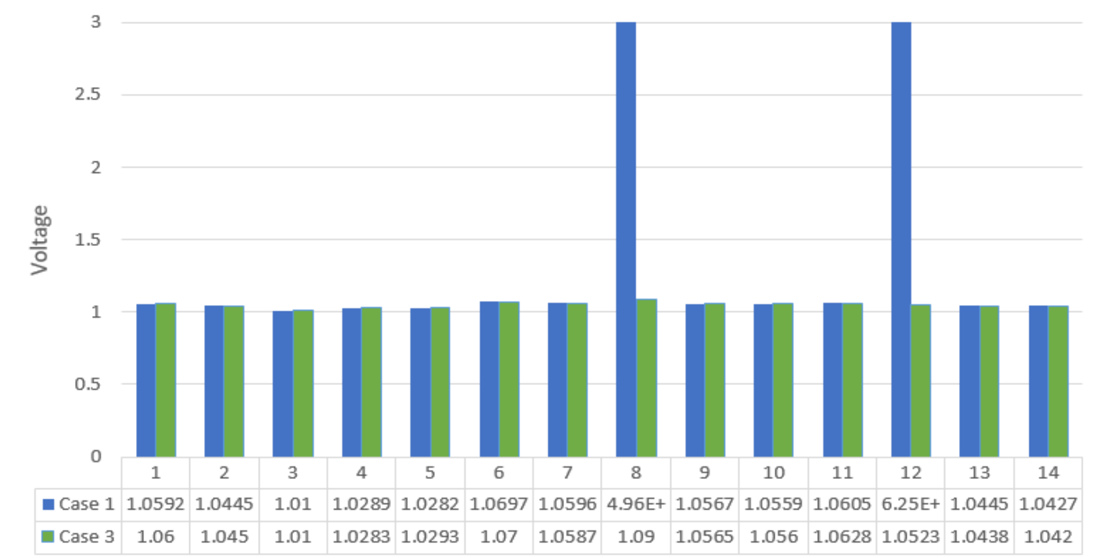


Figure 4.7 Estimated Phase B voltage in Case 1,3

In case there all the phase A values are normal in case three node 8 and 12 shows the singularity. Similarly, rest of the phases voltages are plot in the following graphs.

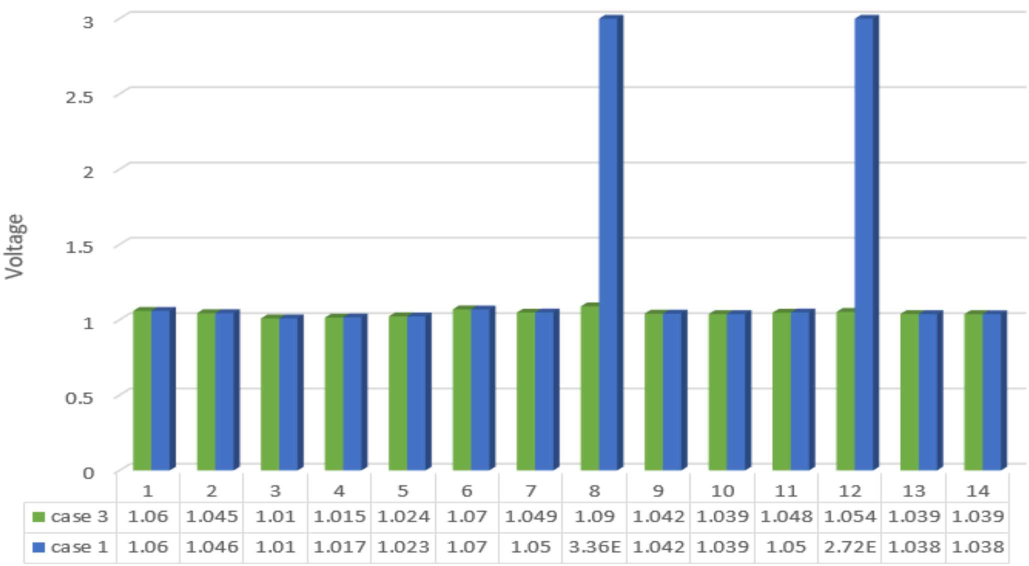


Figure 4.8 Estimated Phase C voltage in Case 1,3

The estimated Voltage magnitudes and the phase angles in degrees are plotted against the respective nodes in all 6 cases in Figure 4.2 and 4.3, respectively. Only in case 6 and case 3 error % is zero or less. In bus 8,11,12 are in correct in most of the cases compare to the actual values SVD shows the significant error. Hence certain bus is unobservable; SVD approach can identify the unobservable island.

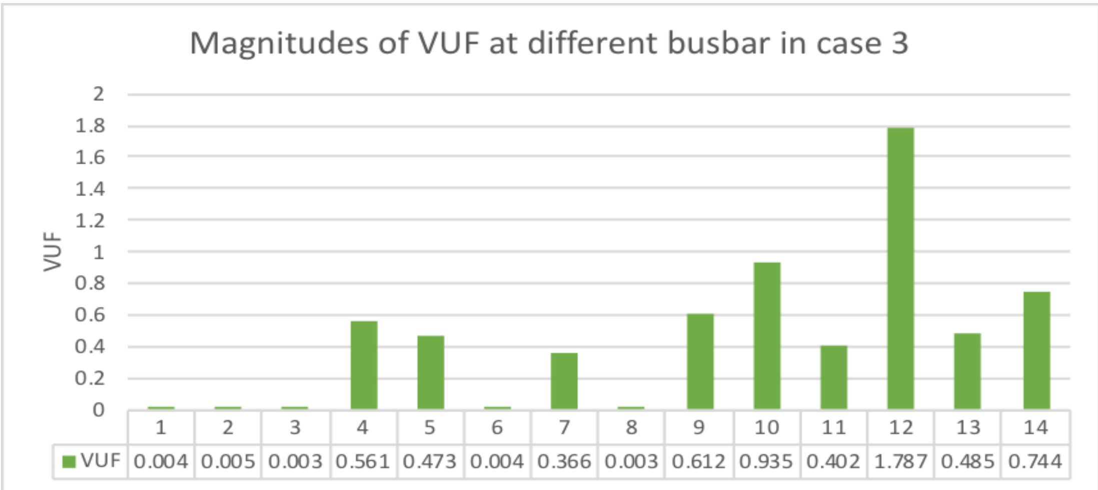


Figure 4.9: Magnitudes and angles of VU factors at different bus bars: IEEE 14 bus test system

VUF obtained using load flow thus verifying the proposed methodology. For voltage controlled busbars (1,2,3,6 and 8), the resultant VUF is equal to zero.

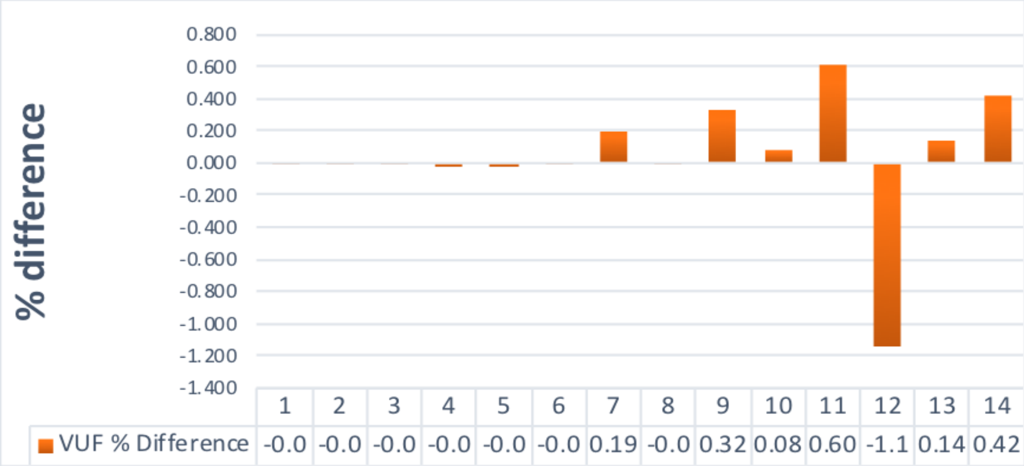


Figure 4.10: Error between the VUF calculated through Load Flow and Estimation Methodology

Further, Figure 4.9 show the graphical representation of the distribution of resultant VUF (magnitudes) at different busbars obtained from the proposed Methodology. The resultant VUFs obtained through formulation and load flow analyses are in close agreement thus demonstrating the validity of the formulation.Difference between the estimated VUF and calculated through load flow shown graphicaly in fig 4.10,maximum error difference is 1.2%.

Table 4.4 : Estimated Voltages in all six cases

Nodes	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	1.06	1.06	1.06	1.06	2.67E15	1.06
	1.0592	1.06	1.06	1.0597	2.98E-15	1.06
	1.0611	1.06	1.06	1.0592	4.29E-15	1.0632
2	1.0456	1.045	1.045	1.045	1.045	1.045
	1.0445	1.045	1.045	1.0447	1.045	1.045
	1.0465	1.045	1.045	1.0454	1.1036	1.0467
3	1.01	1.01	1.01	1.0099	1.0099	1.0099
	1.01	1.01	1.01	1.0098	1.01	1.0099
	0.99888	1.0102	1.0101	0.99774	1.01	0.99902

4	1.0169	1.0153	1.0153	1.0153	1.0153	1.0153
	1.0289	1.0283	1.0283	1.0279	1.0283	1.0283
	1.0372	1.0329	1.0329	1.0343	1.033	1.033
5	1.0231	1.0236	1.0236	1.0236	1.0236	1.0236
	1.0282	1.0293	1.0293	1.0288	1.0293	1.0293
	1.0409	1.037	1.037	1.0406	1.0271	1.037
6	1.0695	1.07	1.07	1.07	1.07	1.07
	1.0697	1.07	1.07	1.0686	1.07	1.07
	1.2182	1.0634	1.0634	1.1443	1.07	1.07
7	1.0497	1.0485	1.0485	1.0485	1.0485	1.0485
	1.0596	1.0587	1.0587	1.0575	1.0587	1.0587
	1.0892	1.0566	1.0566	1.1345	1.0588	1.0588
8	3.36E+12	1.09	1.09	5.06E+12	1.09	1.09
	4.96E+12	1.09	1.09	6.59E+12	1.09	1.09
	8.00E+12	1.09	1.09	6.59E+12	1.0947	1.09
9	1.0418	1.0417	1.0417	1.0417	1.0417	1.0417
	1.0567	1.0565	1.0565	1.0559	1.0565	1.0565
	1.0596	1.0545	1.0545	1.0665	1.0545	1.0545
10	1.0387	1.0387	1.0387	1.0387	1.0387	1.0387
	1.0559	1.056	1.056	1.055	1.056	1.056
	1.0469	1.0497	1.0559	1.0485	1.0491	1.0491
11	1.0496	1.04E+10	1.0483	1.0483	1.1642	1.0483
	1.0605	2.52E+10	1.0628	1.0605	1.1728	1.0628
	1.0474	1.80E+10	1.0557	1.0496	1.1641	1.0557
12	2.72E+12	1.0534	1.0535	1.0535	0.9042	1.0535
	6.25E+12	1.0524	1.0523	1.0509	0.91081	1.0524
	4.10E+12	1.0574	1.0649	1.0559	0.90411	1.0522
13	1.0383	1.0393	1.0393	1.0393	1.0393	1.0393
	1.0445	1.0438	1.0438	1.0432	1.0438	1.0438
	1.0482	1.0549	1.0549	1.0456	1.0548	1.0549
14	1.0382	1.0386	1.0385	1.0386	1.0386	1.0386
	1.0427	1.042	1.042	1.0432	1.042	1.042
	1.0549	1.055	1.0362	1.0542	1.055	1.055

4.3 System Observability Analysis

The test system observability is illustrated by inspection of the relevant factored matrices ([S] and [V]). Calling the MATLAB command [U, S, V] = svd(H) returns three factored matrices U, S,V representing the [H] matrix.

$$[H]_{48x42} = \begin{pmatrix} U_{1,1} & \cdots & U_{1,48} \\ \vdots & \ddots & \vdots \\ U_{42,1} & \cdots & U_{48,48} \end{pmatrix} \cdot \begin{pmatrix} S_1 & & \\ & \ddots & \\ & & S_{42} \end{pmatrix} \cdot \begin{pmatrix} V_{1,1} & \cdots & V_{1,42} \\ \vdots & \ddots & \vdots \\ V_{m,1} & \cdots & V_{42,42} \end{pmatrix}^T$$

S the diagonal entries (Sj) of [S] which are not zero (Sj 's j = 37, 38, ..., 42 are zero). The off-diagonal entries of the matrix [S] are zero. The corresponding columns of [V] whose sj 's (j = 37, 38, ..., 42) are equal to zero are shown in Annexure Basically, the i th (i represents node number) state variable is observable if and only if all the entries of [$v_{i,37}$ · · · $v_{i,42}$] are zero. In [V] corresponding entries at nodes 8,11,12 are non-zero which indicates the un observability of particular nodes and zeros indicates that state variable is observable.

Table 4.5 Busbars and node numbers

Bus Bar	Nodes	Bus Bar	Nodes
1	1,2,3,	14	22,23,24
2	4,5,6	12	25,26,27
3	7,8,9	13	28,29,30
4	10,11,12	6	31,32,33
5	13,14,15	7	34,35,36
9	16,17,18	8	37,38,39
10	19,20,21	11	40,41,42

As tabulated above in S matrix node 37 ,38 to 42 gives Singular values and in V matrix show the non zero values,particular busbar respect to those non zero values nodes are unobservable nodes.In case one Busbar 8 ,11 are unobservable.

CHAPTER 5

5 Conclusions And Recommandations

5.1 Conclusions

Lack of published literature looking into the application of PQSE into voltage unbalance emission assessment, this thesis has successfully reported in this area. Voltage unbalance (VU) has a major impact on the electric utilities and customer loads; hence there are limits on the maximum allowable level of VU. The work carried out verify the precision of the developed Voltage Unbalance State Estimation method in estimating the voltage unbalance states in interconnected networks with unbalanced constant impedance loads. Various cases of loads and lines unbalance are considered for the testing and the validation of the algorithm. A practical consideration on the effect of the locations of the monitoring points on the accuracy of the estimations is also documented in this project. Furthermore, results have shown that the location of the measurements have far more effect on the estimated values.

The developed algorithm requires matrix multiplication and computation of the inverse of matrices containing considerably small numbers. The Singular Value Decomposition (SVD) is a very powerful set of techniques for dealing with sets of equations or matrices that are either singular or else numerically very close to singular. In some cases where Gaussian elimination and LU decomposition fail to provide satisfactory results, Singular Value Decompostion will diagnose precisely what the problem is. In some cases, it will not only diagnose the problem, but it will also solve it, in the sense of giving a useful numerical answer. It is also the method of choice for solving most linear least-squares problems

Singular Value Decomposition (SVD) method, which eliminates the need to use the observability analysis function. This method is also able to give a reliable solution for partially observable systems, which was not possible using the normal equation approach. However, SVD computation is more complex than estimation using the normal equation

5.2 Recommandations

VU emission assessment methodologies only exist for deterministic cases,where the system states are completely known. However, due to cost constraints there are often limitations on the number of monitoring points a utility can afford to place for global assessment. An optimal location of the given number of instruments and monitoring channels, combined with computer system simulation can be used to derive acceptable information regarding the unmonitored locations. This forms the basis of power quality state estimation (PQSE). Nevertheless, this concept has only been discussed with reference to harmonics, transients, and sags [6] in the recent years.

Their are number of Distribution System State Estimation Concept has been discussed in Literature. In order to Develop sort of sophisticated methods to extend Voltage Unbalance State Estimation. In future 'Proposed Voltage Unbalance methodology can be extended using emerging Distribution System State Estimation techniques, which can be used to estimate the level, location and sources of network voltage unbalance. This will facilitate the development of comprehensive Voltage Unbalance assessment techniques.

6 REFERENCES

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7 Appendix 1

Three bus interconnection system data

Phase impedance values in ohm per kilometre & Load impedance connect at busbar 2,3 shown below

$$([Z_{abc}]/km) = \begin{bmatrix} 0.40+j0.40 & 0.05+j0.09 & 0.01+j0.05 \\ 0.05+j0.09 & 0.40+j0.40 & 0.05+j0.09j \\ 0.01+j0.05 & 0.05+j0.09 & 0.40+j0.40 \end{bmatrix}$$

	Phase a	Phase b	Phase c
$[Z_{L2}](\Omega)$	$50+j38$	$60+j19$	$65+j31$
$[Z_{L3}](\Omega)$	$80+j60$	$55+j41$	$60+j29$

	Phase Voltage (kV)			Sequence Voltage (kV)		VUF
	a	b	c	Positive	Negative	(%)
$[V_1]$	$6.27\angle 0.1$	$6.27\angle -120$	$6.27\angle 120$	$6.27\angle -0.14$	$0.01\angle 102$	$0.16\angle 102$
$[V_2]$	$5.90\angle 0.2$	$5.91\angle -121$	$5.95\angle 119$	$5.92\angle -0.88$	$0.05\angle 105$	$0.84\angle 106$
$[V_3]$	$5.95\angle 0.3$	$5.87\angle -121$	$5.90\angle 118$	$5.91\angle -0.75$	$0.04\angle 98$	$0.74\angle 98$

Table 3: Estimated voltages and voltage unbalance factor

	Phase Voltage (kV)			Sequence Voltage (kV)		VUF
	a	b	c	Positive	Negative	(%)
$[V_1]$	$6.27\angle 0$	$6.26\angle -120$	$6.26\angle 120$	$6.58\angle -0.2$	$0.01\angle 40$	$0.13\angle 40$
$[V_2]$	$5.75\angle -0.7$	$5.68\angle -123$	$5.73\angle 118$	$6.01\angle -1.8$	$0.06\angle 43$	$1.0\angle 37$
$[V_3]$	$5.58\angle -1.0$	$5.37\angle -124$	$5.45\angle 117$	$5.74\angle -2.6$	$0.11\angle 31$	$1.9\angle 33$

Table 4: Estimated voltages and voltage unbalance factor

8 Appendix 2

IEEE 14 bus Line Data

```
          |  From |  To   |   R     |   X     |     B/2  | X'mer
|
%         | Bus  | Bus   | Bus    |  pu     |     pu   |  TAP (a)
linedata14 =[1      2       0.01938   0.05917    0.0264        1
             1      5        0.05403   0.22304    0.0246        1
             2      3        0.04699   0.19797    0.0219        1
             2      4        0.05811   0.17632    0.0170        1
             2      5        0.05695   0.17388    0.0173        1
             3      4        0.06701   0.17103    0.0064        1
             4      5        0.01335   0.04211    0.0           1
             4      7        0.0       0.20912    0.0         0.978
             4      9        0.0       0.55618    0.0         0.969
             5      6        0.0       0.25202    0.0         0.932
             6     11        0.09498   0.19890    0.0           1
             6     12        0.12291   0.25581    0.0           1
             6     13        0.06615   0.13027    0.0           1
             7      8        0.0       0.17615    0.0           1
             7      9        0.0       0.11001    0.0           1
             9     10        0.03181   0.08450    0.0           1
             9     14        0.12711   0.27038    0.0           1
            10     11        0.08205   0.19207    0.0           1
            12     13        0.22092   0.19988    0.0           1
            13     14        0.17093   0.34802    0.0           1
```

9 Appendix 3

IEEE 4 bus system Data

The source is a 12.47 kV line-to-line infinite bus.

Closed Connections Load Data:

	Balanced	Unbalanced
Phase-1		
kW	1800	1275
Power Factor	0.9 lag	0.85 lag
Phase-2		
kW	1800	1800
Power Factor	0.9 lag	0.9 lag
Phase-3		
kW	1800	2375
Power Factor	0.9 lag	0.95 lag

Line Impedances

Phase impedance matrix:

$$zd = \begin{pmatrix} 0.4013 + 1.4133j & 0.0953 + 0.8515j & 0.0953 + 0.7266j \\ 0.0953 + 0.8515j & 0.4013 + 1.4133j & 0.0953 + 0.7802j \\ 0.0953 + 0.7266j & 0.0953 + 0.7802j & 0.4013 + 1.4133j \end{pmatrix} \quad \Omega/\text{mile}$$

Sequence impedances:

$$zd_{pos} = 0.306 + 0.6272j \quad \Omega/\text{mile}$$

$$zd_{zero} = 0.5919 + 2.9855j \quad \Omega/\text{mile}$$

Step-Down with Balanced Loading

Standard 30 degree connections are assumed for wye-delta and delta-wye banks

V1 = Vag for wye connections and Vab for delta connections
V2 = Vbg for wye connections and Vbc for delta connections
V3 = Vcg for wye connections and Vca for delta connections

Connection	Gr Y - Gr Y	Gr Y -D	Y - D	D - Gr Y	D - D	Open Gr.Y-D
Node-2						
V1	7107/-0.3	7113/-0.3	7112/-.03	12340/29.7	12339/29.7	6984/0.4
V2	7140/-120.3	7132/-120.3	7133/-120.4	12349/-90.4	12349/-90.4	7167/-121.7
V3	7121/119.6	7123/119.6	7124/119.6	12318/149.6	12321/149.6	7293/120.5
Node-3						
V1	2247.6/-3.7	3906/-3.5	3906/-3.4	2249/-33.7	3911/26.5	3701/-0.9
V2	2269/-123.5	3915/-123.6	3915/-123.6	2263/-153.4	3914/-93.6	4076/-126.5
V3	2256/116.4	3909/116.3	3909/116.3	2259/86.4	3905/146.4	3572/110.9
Node-4						
V1	1918/-9.1	3437/-7.8	3437/-7.8	1920/-39.1	3442/22.3	3384/-3.5
V2	2061/-128.3	3497/-129.3	3497/-129.3	2054/-158.3	3497/-99.4	3804.9/-130.2
V3	1981/110.9	3388/110.6	3388/110.6	1986/80.9	3384/140.7	3246/106.5
Current 1-2						
Ia	347.9/-34.9	334.8/-34.5	335.8/-34.7	335.0/-35.7	335.8/-34.7	380.9/-65.2
Ib	323.7/-154.2	335.4/-154.9	335.9/-154.6	331.8/-154.0	335.8/-154.6	387.4/-125.2
Ic	336.8/85.0	337.4/85.4	335.9/85.3	341.6/85.6	336.0/85.4	0
Current 3-4						
Ia	1042.8/-34.9	1006.6/-64.7	1006.6/-64.7	1041.9/-64.9	1006.7/-34.7	659.3/-65.2
Ib	970.2/-154.2	1006.7/175.4	1006.7/175.4	973.7/175.9	1006.7/-154.6	665.7/175.6
Ic	1009.6/85.0	1007.2/55.3	1007.2/55.3	1007.0/55.0	1007.2/85.4	670.5/54.8
Node 2						
Van			7116/-.03			
Vbn			7131/-120.3			
Vcn			7121/119.6			
Vng			3.6/169.5			

Step-Down with Unbalanced Loading

Standard 30 degree connections are assumed for wye-delta and delta-wye banks

V1 = Vag for wye connections and Vab for delta connections
V2 = Vbg for wye connections and Vbc for delta connections
V3 = Vcg for wye connections and Vca for delta connections

Connection	Gr Y - Gr Y	Gr Y -D	Y - D	D - Gr Y	D - D	Open Gr.Y-D
Node-2						
V1	7164/-0.1	7113/-0.2	7112/-0.2	12350/29.6	12341/29.8	6952/0.7
V2	7110/-120.2	7144/-120.4	7144/-120.4	12314/-90.4	12370/-90.5	7172/-122.0
V3	7082/119.3	7111/119.5	7112/119.5	12333/149.8	12302/149.5	7313/120.5
Node-3						
V1	2305/-2.3	3896/-2.8	3896/-2.8	2290/-32.4	3902/27.2	3632/0.1
V2	2255/-123.6	3972/-123.8	3972/-123.8	2261/-153.8	3972/-93.9	4121/-127.6
V3	2203/114.8	3875/115.7	3874/115.7	2214/85.2	3871/145.7	3450/108.9
Node-4						
V1	2175/-4.1	3425/-5.8	3425/-5.8	2157/-34.2	3431/24.3	3307/-1.5
V2	1930/-126.8	3646/-130.3	3646/-130.3	1936/-157.0	3647/-100.4	3907/-131.9
V3	1833/102.8	3298/108.6	3298/108.6	1849/73.4	3294/138.6	3073/103.1
Current 1-2						
Ia	230.1/-35.9	308.5/-41.5	309.8/-41.7	285.7/-27.6	361.7/-41.0	424.8/-73.8
Ib	345.7/-152.6	314.6/-145.5	315.5/-145.2	402.7/-149.6	283.5/-153.0	440.3/-118.5
Ic	455.1/84.7	389.0/85.9	387.2/85.9	349.1/74.4	366.5/93.2	0
Current 3-4						
Ia	689.7/-35.9	10083.8/-71.0	1083.8/-71.0	695.5/-66.0	1084/-41.0	735.2/-73.8
Ib	1036/-152.6	849.9/177.0	849.9/177.0	1033/177.1	849.7/-153.0	569.9/176.3
Ic	1364/84.7	1098.7/63.1	1098.7/63.1	1352/55.2	1099/93.2	762.0/61.5
Node 2						
Van			7116/-0.3			
Vbn			7142/-120.4			
Vcn			7109/119.6			
Vng			4.27/171.6			

For Estimation comparaison Y-Y connections is considered