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POWER SYSTEM DYNAMIC VARIABLE ESTIMATION WITH PMU

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF

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SUBMITTED BY:

NITISH ARORA

(2K19/PSY/14)

UNDER THE SUPERVISION OF

Prof. S.T NAGARAJAN

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering) Bawana Road, Delhi-110042

DECLARATION

I hereby certify that the work which is presented in the Major Project – II entitled "Power System Dynamic Variable Estimation with PMU" in fulfilment of the requirement for the award of the Degree of Master of Technology in Power System and submitted to the Department of Electrical Engineering, Delhi Technological University, Delhi is an authentic record of my own, under the supervision of Prof. S.T Nagarajan.

The matter presented in this report has not been submitted by me for the award for any other degree of this or any other Institute/University.

NITISH ARORA

2K19/PSY/14

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

SUPERVISOR CERTIFICATE

To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I, further certify that the publication and indexing information given by the student is correct.

Place: Delhi

Date:

Prof. S.T Nagarajan
(Professor)
SUPERVISOR

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Date:

Nitish Arora

2K19/PSY/14

M. Tech (Power System)

Delhi Technological University

ABSTRACT

PMU's have a significant importance in present day power systems. They have a wide applications in the management, protection of power as well as in state estimation. It has been seen that full observability of power system for the available data is required for state estimation. Although, this can be achieved by conformist estimators using bus voltage, real and reactive power flows as well as by power injection data derived from SCADA but with the increasing use of PMU's time harmonized voltage phasors measurement of the bus to which all the branches are incident to that bus can be easily obtained. This characteristic feature of PMU makes the measurements of PMU better than SCADA measurements. However, the high cost associated with PMU's makes their positioning at all the buses unviable. In the present study, a two stage novel algorithm is projected for optimal placement of PMU for wide ranging observability.

The ever-increasing size and intricacy of the power system, monitoring as well as control has become a significant issue for which EMS at the control centre is responsible. State Estimator provides the finest approximation of the current operating state of the system based on the collected set of measurements. The data consisting of power flows, power injections and voltage magnitudes are generally processed by SCADA systems. However with the introduction of PMUs, both voltage magnitude and angle can be calculated that are elements of the state vector as these are time synchronized with the GPS. Consequently, the dynamic view of the power system can be captured more accurately. Hence, the emergence of new technologies in the area of monitoring is imperative. Therefore, the generator rotor speed ω and rotor angle δ are simulated in this dissertation. The dynamic variables are also estimated by EKF method for transient condition on the test system under consideration in a definite time interval. The transient condition is considered and the simulations are performed in MATLAB. The estimated dynamic variables under transient conditions obtained by applying the EKF algorithm and the dynamic variables calculated with the Fourth order Runge Kutta method are compared to depict the efficacy of the algorithm. The performance indices (ε_{ω},ε_{δ}) are also calculated which indicate the accuracy of the EKF method employed to the test system.

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LIST OF ABBREVIATIONS

PMU Phasor Measurement Unit

SCADA Supervisory Control and Data Acquisition

EMS Energy Management System

WAMS Wide Area Management System

ROCOF Rate of Change of Frequency

GPS Global Positioning System

UTC Universal Coordinated Time

VSI Voltage Stability Indices

LSM Least Square Method

IP Integer Programming

LP Linear Programming

BPSO Binary particle Swarn Optimisation

WLS Weighted Least Square

EKF Extended Kalman Filter

LIST OF SYMBOLS

R_k	System noise co- variance matrix
Q_k	Measurement noise co-variance matrix
$\in_k$	Error
$x_0^{\leftrightarrow}$	Initial state
$P_0^{\leftrightarrow}$	State Covariance matrix
K_k	Kalman Gain Matrix
ω	Rotor speed
δ	Rotor Angle
σ	Standard deviation
t	Time instant

CHAPTER 1

INTRODUCTION

1.1 Background

Initially, energy systems were isolated on a small scale. Power stations were located in the vicinity of the load center and operators personally monitored the condition of the electrical equipment and used regulatory measures according to the situation. This method of control depended entirely on the electrical personnel. Human response is not fast enough in an emergency or in the event of a sudden accident, so there is little chance of stopping the danger before it spreads throughout the system. The progress of technological development, the scale of the energy network is constantly growing. Therefore, personal surveillance and deception cannot meet the requirements for a safe and consistent operation of the energy system. A massive generation production, an enormous and comprehensive transmission network needs towering quality assurance of a secure and reliable system. The major purpose of energy generation program is to offer dependable and sustainable energy for all customers without interlude. For attainment of this goal we need a well-developed and smart energy-based system based concurrent data availability. Conventionally, standardized units of measurement provided analog and digital information including power and energy flow, frequency that propelled to load center via controls, analysis units such as SCADA or EMS. They provide phase angle difference among substations under consideration which is made through obtainable facts that are often intended offline which leads to incorrect results. Wide Area Measurement System (WAMS) technology provides an prospect to steer clear of these troubles [1].

1.2 Phasor Measurement Unit:

These fast-paced power gadgets can offer harmonized dimensions of electricity quantities. In recent times, these units are used in power grids, commonly recognized by the wider area Measurement system (WAMS). WAMS is quick power supply structure, capable of providing precise and compatible power grid details in real time [2]. It is well documented that reporting rate of PMUs is very high (30-60 frames/ sec) compared to traditional SCADA system (2-3 frames/sec). It is because of high resolution, the PMU are employed to analyze the vibrant actions taking place in power grid [3]. It calculates the amount and phase angle of the current and electrical energy which can be assessed to scrutinize the power set-up. The active energy flow in the transmission lines is in a straight line proportionate to sine angle difference amid voltages at the two ends of the line. Therefore, the phase angle difference is very crucial for monitoring and control purpose in a power system [4]. There are two most important functions of PMUs. The foremost is converting the analog signal to digital form in order for having idea of phasor quantity of the signal viz. phasors of voltage and current, frequency, ROCOF, circuit breaker as well as switches condition with a concurrent lag and the other is to pass it on to advanced device at regional or distant sites.

Furthermore, harmonization of time is done by GPS based on UTC. Although the estimation part is evolving till date but the transmission has been validated by IEEE standards.

1.3 Phasor Measurement Unit Applications:

Synchrophasor machinery and PMU device were used for the construction of a contemporary energy network, as a result of which the great success of the system such as reliabile and controllable electrical networks have attained a much enhanced stage. In the subsequent sections, various benefits of PMUs into energy systems shall be discussed.

1.3.1 Voltage Stability:

Capacity of power system to uphold stable power on all buses in a system after interruption from given preliminary constant state is called as Voltage stability. There are diverse forms of voltage stability known as discussed in [5]. The machinist uses Voltage Stability (VSI) Indices to establish how much time the system will take to crumple the voltage or the manner in which it can be supplied to the load. The records of PMU assists to envisage energy unsteadiness concurrently to achieve improved control measures to evade cascading collapse. A range of methods of visualizing and analyzing state of voltage unsteadiness using Real Time PMU information has been well recorded [6-10].

1.3.2 State Estimation:

This is also recognized as filtering that utilizes the redundancy of real- time measurements to amend the closeness and to remove the bad data caused by arbitrary noise. By doing so the operating state of the system can also be estimated. As a modem computer real- time processing form, it can be applied primarily to the field of chasing and control of spacecrafts, satellites, guided caps and submarines. The basal hypothesis is a recursive close filtering form which is proposed by Rudolf E. Kalman [11]. This form only needed to remember the estimation value at the anterior time and the measurement value at the current time. Although, the dimension of the state vector of power system is comparatively high, but it becomes hard to bag the statistical data. Hence, one ordinarily and accepted way of assessment is the least square method (LSM).

1.3.3 Detection of Fault

At present, significant efforts have been made in investigating and developing new technologies that differentiate errors that occur in overhead transmission lines. Errors that occur in the system can be broadly classified into permanent and temporary error. Permanent errors occur as a result of events like out of order line or malfunction of power generators. Interestingly, the temporary error are usually caused by the insulator flashover will not cause the breakdown instantly. In any case, flashover of insulators may promote a complete deterioration of the protector when such temporary events persist [12] - [14].

It is important to protect and dismantle the whole scheme and you need to recognize the error to the fore of time. The PMU-enabled error technique is able to measure error site with the corresponding voltage error values as monitoring of transmission lines is by node placement of PMUs. This can be done to measure the flow of line currents amid these nodes. Based on the current path measurement of the node injection current error can be done at both ends of the terminals. The current limited error node injection, fault nodes elimination, defective areas in the transmission lines can be accurately determined [15] [16]. A flow chart depicting PMU based fault detection is represented in Figure 1.1.

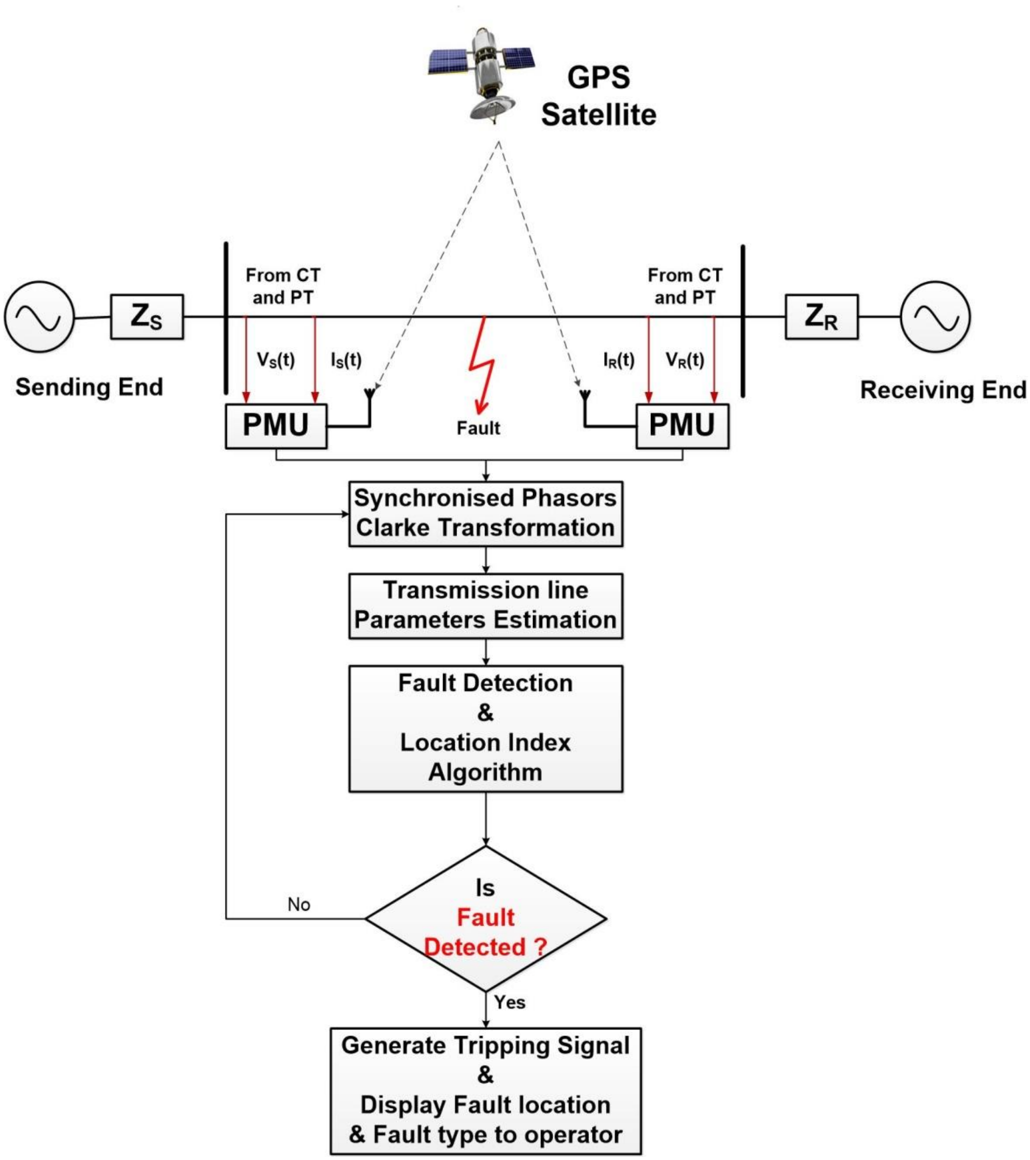

Figure 1.1: A line diagram for PMU based detection of fault

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction:

Speedy stride in world population has proportionally increased the requirement for reliable energy. The network of transmission and distribution has played crucial responsibility in transmitting power from generating stations to load centers. In order to thwart power loss, utmost care should be laid on the quality and the stability of the various components monitoring and measuring machines used in power transmission network. The use of synchronized GPS clock in the phasor measuring unit can calculate large amounts of information on critical power network, including bus power, current, generator speed and power angle. The trained persons in center of operation can supervise very easily, scrutinize & explore value of supply network in stationary and vibrant working circumstances if PMU real-time measurement are installed at broad areas. Similar studies have been conducted by Phadke A. G. [17] who also found that installation of PMUs at substations can greatly pick up the trustworthiness of the power connections.

2.2 PMU and its Optimal Placement:

It has been observed that as the cost of single PMU device is $ 19,500 USD [18] therefore it is not financially viable to attach these at all the buses. For limiting the number, repair, unit costs and increase the power set up observability, a very effective optimization is required. In modern era, a new perspective of research is to focus on the placement of PMU at optimized position. The most familiar OPP algorithms methods used to tackle with the positioning of PMU to have its best output are Heuristic Method, Meta-Heuristic Method and Deterministic Method [19]. Diverse categories of available and prominent algorithms are given in Table 2.1[20-33]

Table 2.1: Classification of Algorithms

Heuristic Method	Meta-Heuristic Method	Deterministic Methods
Depth-First Algorithm (DFS) [20-21] Domination S [22-23] Greedy Algorithm [24]	Genetic Algorithms [25-26] Particle Swarm Optimization (PSO) [27-29]	Integer Programming [30-32] Binary Search Method [33]

It has been observed that bisecting exploration and simulated annealing based methods along with non dominated sorting based genetic algorithm approach [35], replicated annealing based graph theoretic approach [36] and IP based approach [37-38] play major role in PMU placement area [34]. Among all the approaches used in the random positioning of PMU, it has been reported that IP approach is better over bisecting exploration [39]. It has been observed that branching causes the development of sub problem of the novel predicament and bound causes listing of the sub problem via linear programming. In this process LP solver is required in every iteration that too based on the dimension of the system which is computationally intensive. It has been documented that although binary search method is exhaustive and suitable for making a best global elucidation but for large size networks a heavy computational burden is required [40]. Therefore, scheme of PMUs is proposed in a phased installation so that the final position will be optimal [41]. It has been reported that Tabu exploration metaheuristic technique is best to decrease the number of PMU to enhance its effect in power scheme [42]. Furthermore, to solve the problem of the multi-objective optimization of PMU positioning, a non-dominated sorting based differential evolution algorithm is proved to be the best [43]. On the contrary, the metaheuristic based iterative local search method has been projected to unearth the best possible answer for initial PMU placement to make it entirely discernible [44]. A two stage PMU placement method is anticipated in which the stage-I deals with topological and stage-II with arithmetical observability that too heavily increases the computational burden [45]. Binary particle swarm optimization based approach has been designed to minimize the PMU number as well as increase the measurement redundancy [46].

The modified BPSO as well as contingency constrained methods has also been reported to deal with the positioning of PMU [47-49]. It has been reported that heuristics based optimal PMU placement method solve the issue of zero injection bus [50]. The reports indicate that SCADA measurements can well be used for selection of optimal PMU to reduce the loss [51].

2.3 PMU and State Estimation:

It has been shown that a vital element of EMS is the accurate and computationally fast state estimation. Two broad categories of state estimation i.e. Static and dynamic are available. The available measurement set can not give any clue of the future state of the energy system using stationary state estimation. Conversely, dynamic state estimation models help the state vector to be predicted in advance owing to the time varying character of the power system. This distinguishing feature enables the monitoring, manage and firmness investigation of the electrical power scheme. The improvement in transfiguring of state estimation process has become possible only with the prologue of PMU based high speed and synchronously sampled measurement systems.

The review of literature reveals that to predict the flow of reservoir and the load supply Kalman filter method had been used in 1968 by Japanese engineers [52]. It was for the first time that the state estimation was practically employed in power systems. Furthermore, the weighted least squares method (WLS) having good convergence properties was used by F.C. Schweppe in 1969 [53]. The drawback of this method was that it led to complex calculations that take up enormous computer space to congregate the condition of complex calculations. This predicament becomes more severe in huge power systems. To ascertain a quick decoupled method of state estimation based on WLS, the power flow calculations were used by H. P. Honsberger [54]. It has been predicted that the application of algorithm enhance the computation speed, convergence, memory space as well as adaptation to various kinds of capacity values. J. F. Dopazo [55], an engineer from American Electric Power Service Corporation. has described the possibility of enforcing the state estimation algorithm. He found that compared to the original WLS, the new method is faster, utilizes smaller space and easier code. Although, it is tough to deal with the injected measurement value at the node, but still the practicability is very high. Likewise, R. E. Larson [56] from American Bonneville Power Administration projected a recursive assessment algorithm on basis of Kalman filter.

But the method used the diagonalizable covariance matrix of analysis due to high dimension of state vector in power system. The technique also helped to decrease the convergence as well as quality of estimation in spite of saving space and enhancing the computation speed. Since then, several·countries such as Sweden, France, Japan, Australia; England and Italy lucratively researched more advanced framework of state estimation. The foremost rationale of state assessment methods was the small network of Norwegian Power Administration (Tokle) and the large network of American Electric Power (AEP). By 80s, a number of power networks were developed their effectiveness had gained a good standing. Over the years of research the scientists have been able to achieve many milestones in the field of power state estimations from its birth to present. A proper documentation of major research achievements power system state estimation between 1968 and 1989 have been made by M. B. Do Coutto Fitho and A. M. Leite da Silva [57]. It has been observed that the research directions and methods have changed at the end of the last century. A comparision in terms of similarities and differences of traditional over modern power system state estimation has been made by A. Moncelli [58]. The common parameters between residue sensitivity and Kalman filter method were pointed out by Pedro Zarco [59]. With the rapid stride in communication, computer and space technologies, PMU, the first device based on the GPS was developed in 1988. It provides a immense support to the development of inspection, maneuver and security of modem power system. The major edge of PMUs is that it can scrutinize the operating state of the power scheme concurrently. R. Zivanovic and C. Cairns [60] worked on outline of PMU alone as well as combination of PMU and SCADA and exhibited that how the results can be applied in power system.

CHAPTER 3

ORIGINAL ALGORITHM FOR MOST FAVORABLE PMU POSITIONING FOR BROAD RANGE POWER SYSTEM OBSERVABILITY

3.1 Introduction:

PMU’s have a noteworthy role in contemporary power systems.Their role is magnificent in state estimation, power system protection, monitoring and control. The state estimation- an indispensable component of EMC require full observability of power system for the available data [61]. The synchronized state of the power system was calculated by conservative estimators using bus voltage, real and reactive power flows, power injection data derived from SCADA. However, with the increasing use of PMU’s time coordinated voltage phasors dimension of the bus to which the PMU is connected with corresponding current phasor so that bus can be easily obtained [62].This characteristic feature of PMU has edge over SCADA measurements. Consequently, the position of PMU’s in the buses of power network has direct influence exclusive of the stipulation of state estimators.

The PMU and communication system has very high cost which limits its installation in every bus/node of the power system. There there is urgent need to look for alternatives so that it can be used optimally. In light of this, a novel algorithm is anticipated to design topological observability with minimum use of PMU by improvement of its angle of placement. There are two stages involved in the proposed algorithm. The foremost is to add PMU in bus having highest number of branches connected to it. Its addition is sustained until the restraint vector utility linked to optimization is resolved. After this, the exclusion stage is initiated i.e. the bus linked with next bus in the set power association. Placing least quantity of PMU’s at tactical sites that provide maximum observability, diminution of multiplication velocity and increasing the precision are the critical objectives.

3.2 Power System Observability Analysis and Rules:

The available measurements indicate that for the better operation of power structure state estimation, Total network observability has very crucial role. Both voltage and current flows of the associated bus makes it observable. Therefore, in order to have absolute power system observability, each and every bus must be entirely observable by making use of either direct or indirect dimensions. Numerical or topological techniques can be used for observability evaluation. Consequently, if the system has to be discernible, design matrix H is mandatory to be of full rank [63]. On the contrary, a topologically observable system needs at least one crossways dimension tree to be of full rank [64]. The following points has to be kept in mind to increase observability of each bus:

Rule 1: PMU fitting in bus gives undeviating assessment of voltage phasors of linked bus and the current phasors of incident branches.

Rule 2: If two buses are linked by branch, then voltage phasors of any one bus can be calculated with a condition that voltage phasor of any one and current phasor of the branch incident to a bus is available.

Rule 3: On recognition of dimensions of voltage phasors of two buses connected via branch are predicted, then current phasors of the incident branch can be measured

The whole scheme observability of IEEE 9-bus employing the above rules has been depicted in Figure 3.1.

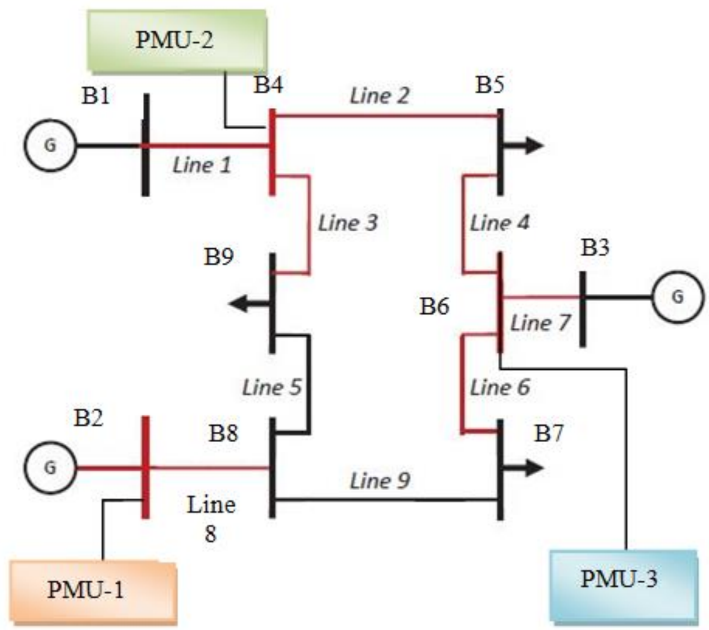

Figure 3.1: 9-bus system (IEEE)

According to Rule 1, the positioning of PMU at B2 indicate the dimensions of voltage phasor at B2 and current phasor matching to line 8. Consequently, B2 is visible unswervingly. Furthermore, Rule 2 implies that although voltage phasor of B8 can be measured but is visible in a roundabout way. On the otherhand, if PMU is placed at B4 then the incident B1, B5 and B9 will also be clearly discernible. It is further noted that through line 5, the Current phasor can also be premeditated following Rule 3. Likewise, by positioning PMU at B6, then the B3, B5 and B7 can also be seen in an indirect way. In addition, the Rule 3 can also help to analyze Line current via B8. It has also been observed that installing 3 PMU's, the whole power system become totally visible. Nevertheless, identifying PMU site (B2, B4 and B6) needs lots of efforts in terms of diverse permutations and combinations and has been explained in proceeding sections.

3.3 Problem Formulation :

Optimization problem for PMU in N bus system is formulated as:

minimize $\sum_{i=1}^{N} w_i \; x_i$

such that G(X)≥b (3.1)

Here ‘X’ denotes the binary decision variable vector and G(X) represents the constraint function. The present study, for deciding the optimum locations for placement of PMU, can be formulated as zero one problem. The presence or absence of the PMU at a particular location can be denoted by 1 or 0 respectively. The entries of ‘X’ are as:

$$x_i = \begin{cases} 1, \text{ if the PMU is placed at the } i^{th} \text{ bus} & i=1,\ldots,N \\ \text{zero, otherwise} \end{cases} \tag{3.2}$$

b==$[111\cdots]^T$ depicts a unit vector of size N. Considering the installation cost of all the PMU’s installed in the power network same and the value is taken as 1 per unit, then the optimization problem formulation can be done as:

Minimize $\sum_{i=1}^{N} x_i$

such that G(X)≥ 1

(3.3)

Full network observability is ensured by constraint vector function. A minimum set of xi is found that satisfies Equation (3.3). Since PMU installation at a bus can provide current phasor of the branches incident to that bus apart from the voltage phasor, hence voltage phasors of the nearby branches can be computed. Hence the matrix [A], representing bus connectivity information, can be obtained having elements as below:

$$A_{ij}=\begin{cases} 1, \text{ if i=j or if bus I and j are connected} \\ 0, \text{ otherwise} \end{cases} \qquad (3.4)$$

The product of matrix [A] and [X] results in constraint function G(X)

$$G(X) = AX \geq 1 \qquad (3.5)$$

$$f_i = a_{i,1}x_i + \cdots + a_{i,i}x_i + \cdots a_{i,N}x_N \qquad (3.6)$$

f_i , the object function, is observable if any x_i that appears in f_i is non zero. The system becomes completely observable if all the f_i appearing in F are non zero.

3.4 Proposed Algorithm for placement of PMU:

The focus of the present study was to make the whole system totall discernible with least number of PMU's. This objective was achieved in two steps i.e via optimizing the position of PMUs and by recognizing the bus having highest number of branches linked to it.. To fulfill the purpose, various permutation and combinations were tried till the control vector function is satisfied (5). To manage it numerically, various parameters were changed. It led to the reduction of entire columns of bus connectivity matrix A matching to x_i=0 in (5). Furthermore, rows and columns analogous to variables set to 1 can be dropped. Suppose x_i has been set to '1', now if a_{ji}=0 then the value of x_i=1 has no significance as $a_{ji}x_i$=o whether x_i=1 or 0.

In the exclusion stage, PMU's are detached initially from radial buses and then slowly are replaced in the same which make them visible. This is continuously done up to the maximum valency bus. Again the process is repeated to remove the PMUs from bus and continues till the system becomes totally indiscernible. The algorithm used in the present study give an ample opportunity for positioning PMU with alike least number of them. Conversely, the best way to achieve better results of discerniblity is to select the one with maximum number of branches.

It gives unneeded dimensions that which helps in high-quality state estimation. The superfluous measurement calculation is shown as :

$$\text{Redundancy} = \sum_{i=1}^{N} sum(f_{i(k)}) \tag{3.7}$$

Where f_i denotes the object function, k represents the optimal solution obtained and N denotes the sum count of buses in the network under consideration.

Flow charts for proposed two stage algorithm are detailed in Figure 3.2 and 3.3.

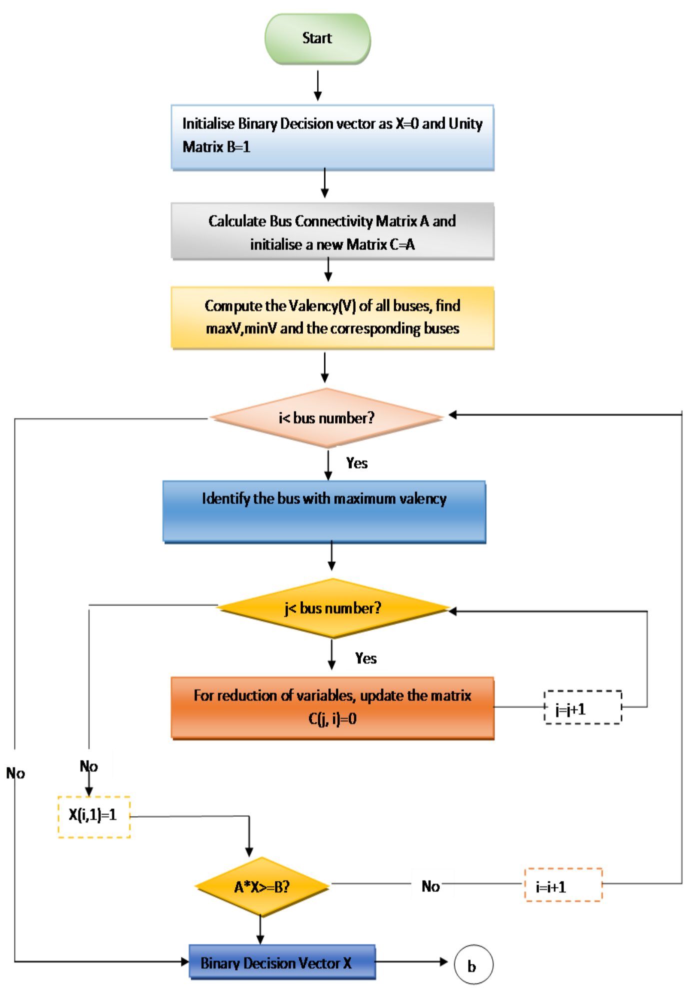

Figure 3.2: Schematic representaion of Stage 1

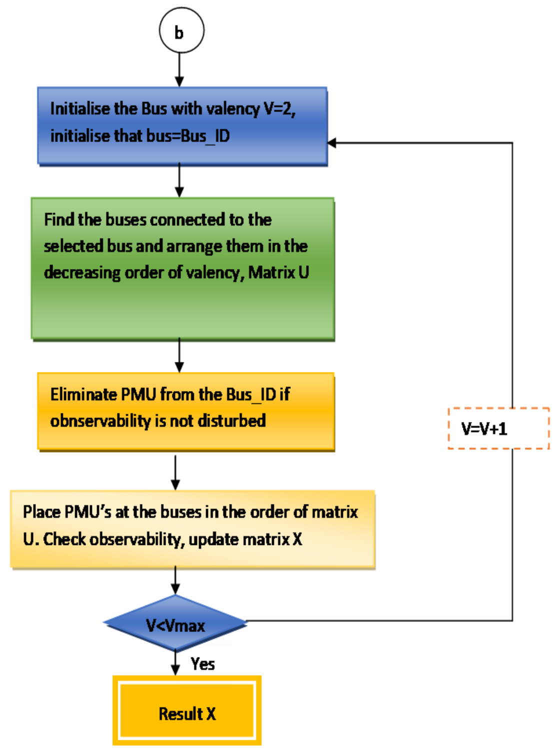

Figure 3.3: Schematic representaion of Stage 2

3.5 Results:

The present study entails the use of different networks to evaluate the numerical efficacy of the algorithm. The outcome of judicious number of PMU's along with best possible bus locations has been documented in Table 3.1.The results obtained by the proposed algorithm has been compared with the methods described in literature [36],[40]and [44]. The pictorial representation in Fig.3.4 shows that the current investigation corroborate with techniques in literature. Furthermore, computational time taken by the projected algorithm is shown in Table 3.2.

Table 3.1: Optimal Location and Numbers Of PMU For Various Test Cases

Test System	Optimal location of PMU	Optimal numbers
IEEE -14 bus	B2, B6, B7, B9	4
IEEE- 30 bus	B3, B5, B6, B9, B10, B12, B18, B24, B25, B27	10
New Egland-39 bus	B2, B6, B9, B10, B13, B14, B17, B19, B20, B22, B23, B25, B29	13
IEEE-57 bus	B1, B6, B9, B15, B19, B22, B25, B27, B29, B32, B36, B38, B39, B41, B47, B50, B53	17

It has been further seen that the projected algorithm has the countless options for positioning of of PMU without increasing its number with diverse number of discernible branches. As a result, it provides superfluous dimensions with good state estimation. On the contrary, the demand of Current Transformers amplify by escalating observable branches and accordingly rising the price. For this reason, the planned algorithm also offers more options for PMU locations when fewer observable branches are necessary consequentially reduction of C.T's. The diverse options and the number of observable branches in bus system IEEE 30 and New England 39 are shown in Figures 3.5, and 3.6 .

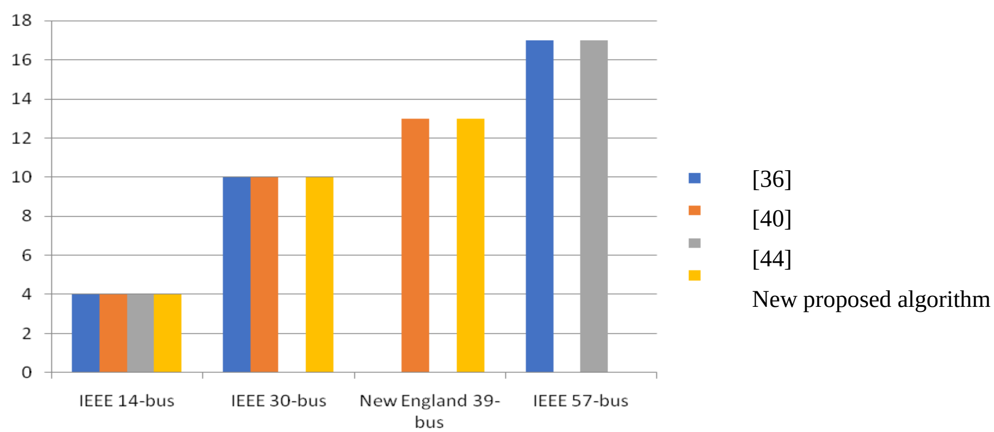

Figure 3.4 Comparison of results with available techniques in literature.

Table3.2: Computational time (in seconds)

Test System	Computational Time(in sec)
IEEE 14-bus	0.034308
IEEE 30-bus	0.047533
New England 39-bus	0.076281
IEEE 57-bus	0.22635

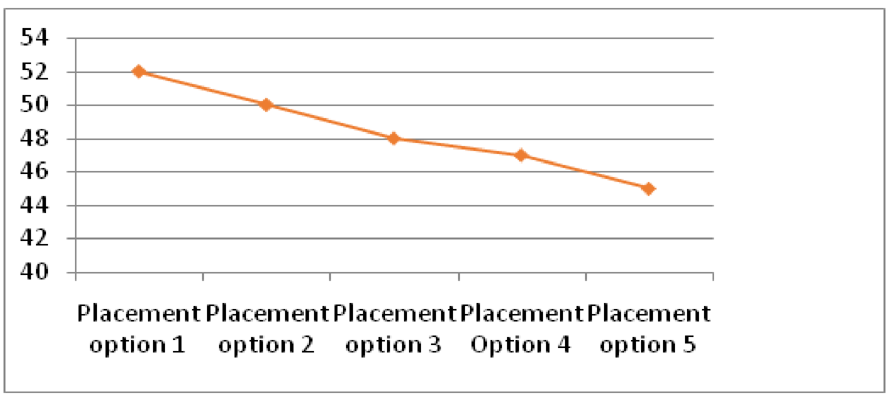

Figure 3.5:Various options of PMU placement and number of observable branches for IEEE 30-bus system

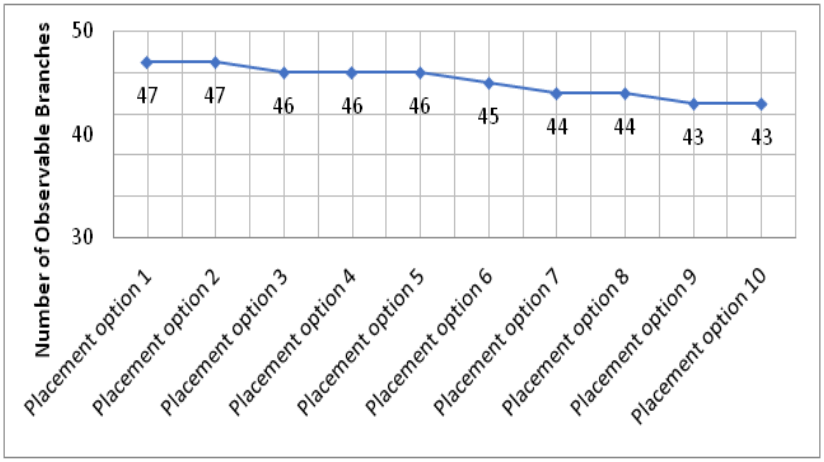

Figure 3.6: PMU placement options and number of observable branches for New England 39-bus system

3.6 Conclusion

The current investigation offers a unique algorithm in which the observability is enhanced and the cost is reduced by using least number of PMU's. Furthermore, it is proficient, high-speed simple and unproblematic to put into operation. The outcome of the study provides efficiency of algorithm for diverse investigation systems with least number and best possible positions of PMU's with improved system observability and computational effectiveness.

CHAPTER 4

POWER SYSTEM DYNAMIC VARIABLE ESTIMATION IN TRANSIENT CONDITIONS USING EXTENDED KALMAN FILTER

4.1 Background:

With the ever increasing size and complexity of the power system, monitoring and control has become a significant issue for which EMS at the control centre is responsible. State Estimator, the core of EMS, provides the optimal estimate of the current operating network on the basis of collected dimensions of the model assumed. The need of the desired state is an important contributing factor based on which the power system estimation problem is formulated as static or dynamic. Static state estimation provides the state vector, consisting of voltage magnitude and angle, for the instant's' of time from the dimension of information available. The variations in load necessitate the adjustment of generators feeding the power system consequently changing the power injections and power flows hence making the power system dynamic. For monitoring continuous dynamic changes in power systems, vibrant condition estimation is done as the static state estimators do not capture the dynamic view of the system under consideration accurately. Dynamic state estimators predict the system state one time step ahead that is't+1'instant of time. Hence, Dynamic state estimators have a forecasting ability. The measurement data consisting of power flows, power injections and voltage magnitudes were collected by SCADA systems. However with the introduction of PMUs, both magnitude as well as angle of the related voltage phasor which are the elements of the state vector can be calculated. Furthermore, PMU's are time synchronized with the GPS. Consequently, the dynamic view of the power network can be captured more accurately. Hence, the emergence of new technologies in the area of monitoring the power system has made the dynamic state estimation imperative. The magnitude of advantage that Dynamic estimation provides in the area of monitoring and control, especially with the usage of PMU's, has been extensively discussed in the literature [65-67].

Methodologies regarding formulation, computational procedures, calculation of state estimates and identifying the modeling errors have been offered in the literature. A method for recognition and detection of data not desired and sudden state variations has been evolved [68]. Estimations through Kalman filtering theory by combining the dynamic model with the linear measurement equations has been proposed in the literature [69]. Kalman filtering algorithm is a two stage algorithm. State parameters are estimated in first stage followed by estimation of state vector in the next stage [70]. However, Kalman filtering algorithm is a recursive filtering method. Kalman filter is a linear estimation method whereas the power system is non linear system. Hence Extended Kalman filtering method based on linearization of non linear equations is used for power system dynamic state estimation. Dynamic state estimation using Extended Kalman Filter (EKF) is investigated in this project. The EKF algorithm is functional to dynamic state estimation of state variables for IEEE 14 bus system.

4.2 Extented Kalman Filtering Algorithm:

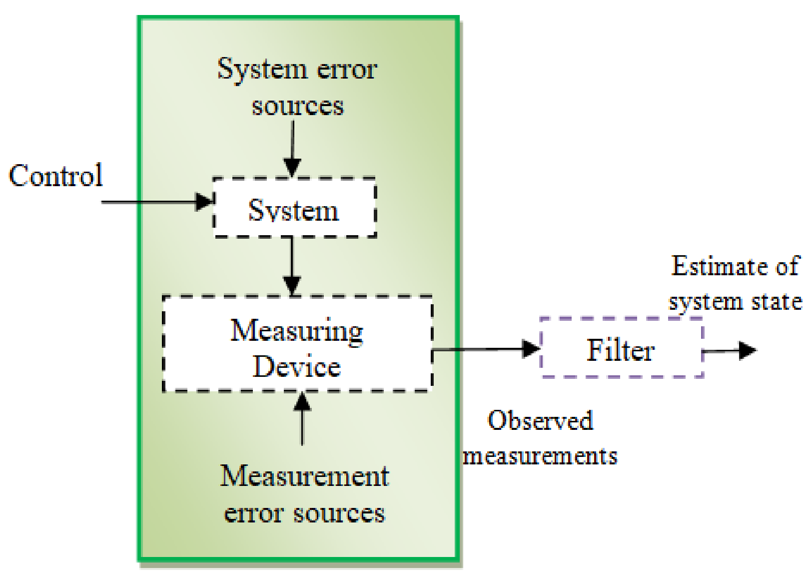

Figure 4.1 Application of Filter

A physical system (like power system) is driven by some external inputs or controls and various measuring devices evaluate the output of the system under consideration. The observations thus obtained indicate the system and the measurement errors. The state estimate is obtained from the available control inputs and the observations. This role is played by the filter. The Figure 4.1 illustrates the application context in which the EKF is used.

4.3 Mathematically modeling:

Mathematically modeling of the dynamic performance of the electrical power arrangement is essential for dynamic state estimation. The dynamic state vector can them be predicted by using the measurement set and the mathematical model obtained with the help of Dynamic state estimator. The dynamic system is generally represented by a non-linear differential equation Equation (4.1).

$$\frac{dx}{dt} = f(x, b, c)$$

(4.1)

Where f (.) represents the system function, a and b corresponds to state and algebraic variables respectively and c denotes the system noise. Equation (4.2) represents the difference form of the equation (4.1) where'Ⴇt-1' and 't' is the present and the next instant of time respectively.Δt corresponds to the time step.

$$a_k = a_{k-1} + f(x_{k-1}, b_{k-1}, c_{k-1})$$

$$a_k = h(x_{k-1}, b_{k-1}, c_{k-1})$$

(4.2-4.3)

$$c_k \sim (0, Q_k)$$

(4.4)

R_k is the system noise co- variance matrix.

The measurement set at the 't' instant of time can be represented by a non-linear function g (.) as in equation (4.3).

$z_k = g(x_k, v_k)$
(4.5)

$v_k \sim (0, R_k)$
(4.6)

Q_k is the measurement noise co-variance matrix.

Here v_k is the measurement noise. The error ($\in_k$) is represented in Equation (4.7).

$\in_k = z_k - g(x_k, v_k)$
(4.7)

All the dynamic state variables cannot be measured directly; hence there is a need to estimate them. EKF method can be applied to estimate the state variables which are in non linear differential equations. EKF method is a two stage estimation method involving prediction and correction steps. At the outset, initialization of the filter is performed.

$x_0^{\leftrightarrow} = E(x_0)$
(4.8)

$P_0^{\leftrightarrow} = E[(x - x_0^{\leftrightarrow})(x - x_0^{\leftrightarrow})^T]$
(4.9)

$x_0^{\leftrightarrow}$ and $P_0^{\leftrightarrow}$ represent the initial state and state covariance matrix. These are the posteriori estimates. In the prediction state the partial derivative matrices are computed at the current state estimate $x_{k-1}^{\leftrightarrow}$:

$F_{k-1} = \frac{\partial f_{k-1}}{\partial x}\bigg|_{x_{k-1}^{\leftrightarrow}}$
(4.10)

$L_{k-1} = \frac{\partial f_{k-1}}{\partial c}\bigg|_{x_{k-1}^{\leftrightarrow}}$
(4.11)

The error co-variance matrix and the state that is estimated are time updated(Equation 4.12,4.13).

$$P_k^- = F_{k-1}P_{k-1}^{\leftrightarrow}F_{k-1}^T + L_{k-1}Q_{k-1}^{\leftrightarrow}L_{k-1}^T$$
(4.12)

$$x_k^- = f_{k-1}(x_{k-1}^{\leftrightarrow}, b_{k-1}, 0)$$
(4.13)

The superscript – denotes the priori estimate.After the prediction, the correction stage follows where the partial derivative matrices [H] and [V] are calculated at the state update.

$$H_k = \frac{\partial h_k}{\partial x}\Big|_{x_k^-}$$
(4.14)

$$V_k = \frac{\partial h_k}{\partial v}\Big|_{x_k^-}$$
(4.15)

Finally the measurement update of state estimate and the estimation co- variance is performed as in Equation[4.16-4.18].

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + V_k R_k V_k^T)^-$$
(4.16)

$$x_k^{\leftrightarrow} = x_k^- + K_k(y_k - h_k(x_k^-, 0))$$
(4.17)

$$P_k^{\leftrightarrow} = (I - K_k H_k)P_k^-$$
(4.18)

Where K_k is the kalman gain matrix, $x_k^{\leftrightarrow}$ and $P_k^{\leftrightarrow}$ are the state estimate and estimated error co-variance matrix respectively.

4.4 Simulation Studies And Results:

The estimation of power system dynamic variables like generator rotor speed ω and rotor angle δ are simulated for IEEE 14-bus system. The dynamic variables are also estimated by the EKF method for transient condition on the test system under consideration in a definite time interval. The measurement set includes the real and reactive power injection, voltage magnitude and the angle. The system and the measurement noise are assumed to be random Gaussian noise of mean equal to zero and standard deviation of $\sigma = 10^{-2}$.The initial values of the state estimation vector are arbitrarily chosen. The results are obtained by applying the EKF algorithm. The accuracy of the estimated values of the state variables by EKF is checked with the calculated values obtained from Fourth order Runge Kutta method. For the IEEE 14 bus test system (Figure 4.2.) the transmission line 3-4 is removed (Figure 4.3.). For this transient case it is assumed that the line is removed at t= 2 sec. The time step is taken to be 0.01sec.The base is assumed as S_{base}=100 MVA and the system frequency is taken as 50 HZ for the simulations performed. The dynamic data for IEEE 14- bus 5 generator system is given in Table 4.1. The estimated dynamic variables and the theoretical values of the test system under the transient condition are represented in Figure 4.4 - 4.12. The estimation error for the generator rotor speed and angle is calculated using equation [4.19] and [4.20] respectively.

$$\varepsilon_\omega = \frac{1}{k_{max}} \sum_{k=1}^{k_{max}} [1/n \sum_{i=1}^{n} |\overline{\omega}_k^i - \omega_k^i| \tag{4.19}$$

$$\varepsilon_\delta = \frac{1}{k_{max}} \sum_{k=1}^{k_{max}} [1/n \sum_{i=1}^{n} |\overline{\delta}_k^i - \delta_k^i| \tag{4.20}$$

Whereω_k^i and δ_k^i are the estimated state vectors. The corresponding values of ε_ω and ε_δ is 2.8657x 10^{-4} and 0.0183 respectively.

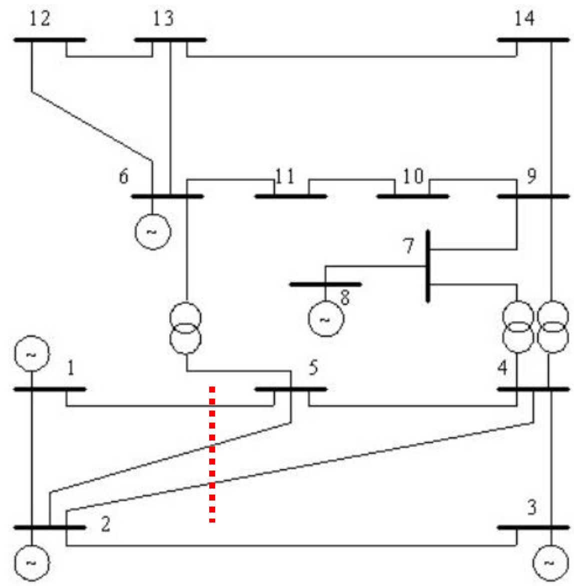

Figure 4.2: IEEE 14- bus test system

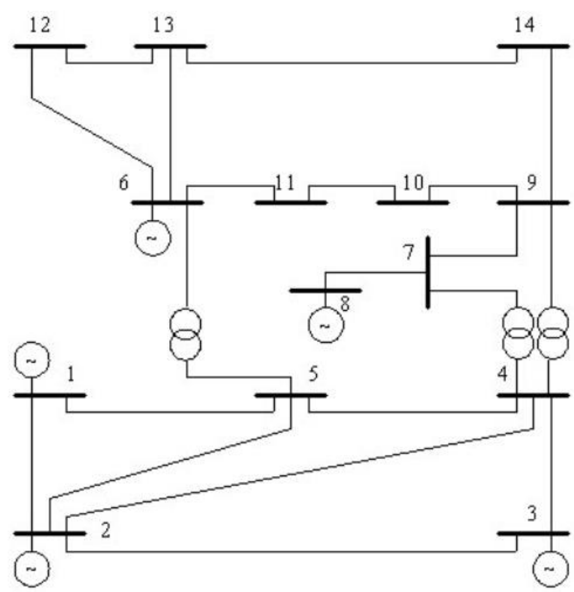

Figure 4.3: Transient case under which transmission line 3-4 is removed at t=2 sec.

Table 4.1: dynamic data of generators of ieee 14-bus test system

Parameter	G1	G2	G3	G4	G5	Unit
X_d	0.2995	0.185	0.185	0.232	0.232	p.u.
H	5.148	6.54	6.54	5.06	5.06	S
D	2	2	2	2	2	p.u.

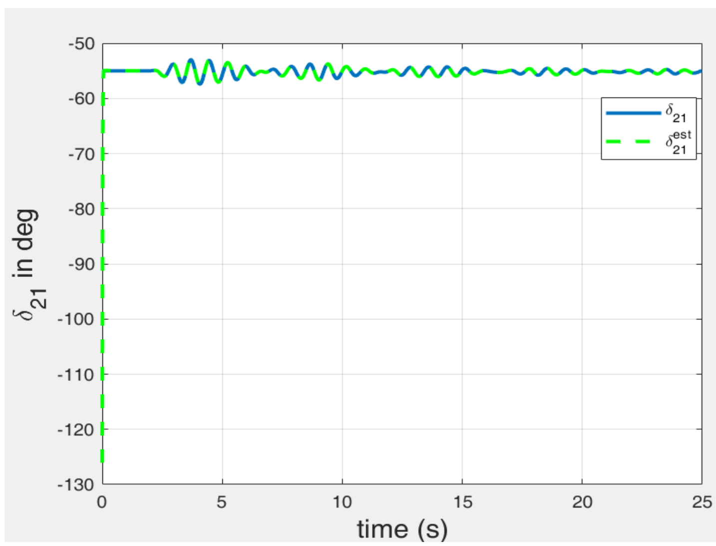

Figure 4.4: δ_{2-1} estimated by EKF and theoretical value

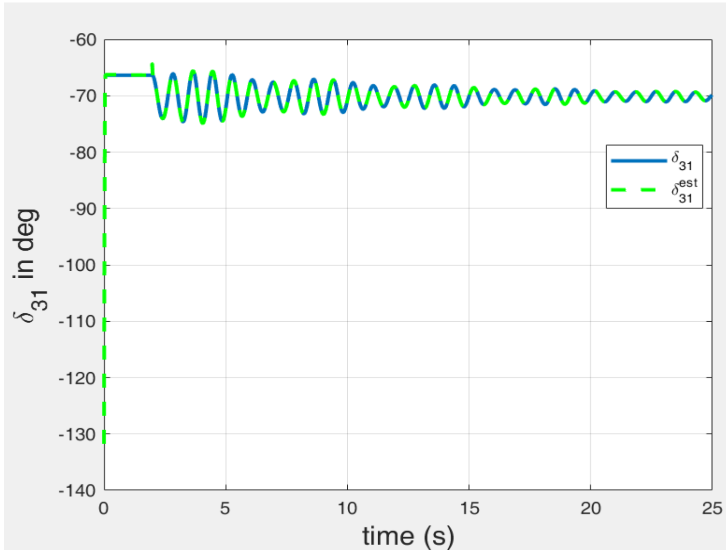

Figure 4.5: δ_{3-1} estimated by EKF and theoretical value

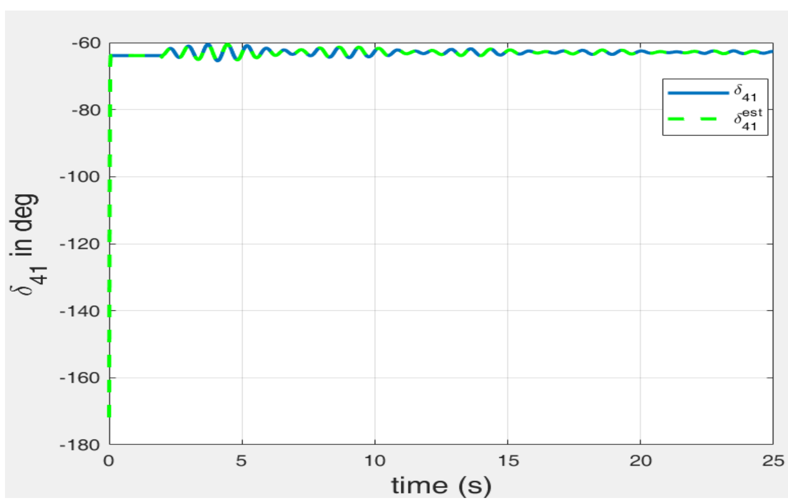

Figure 4.6: δ_{4-1} estimated by EKF and theoretical value

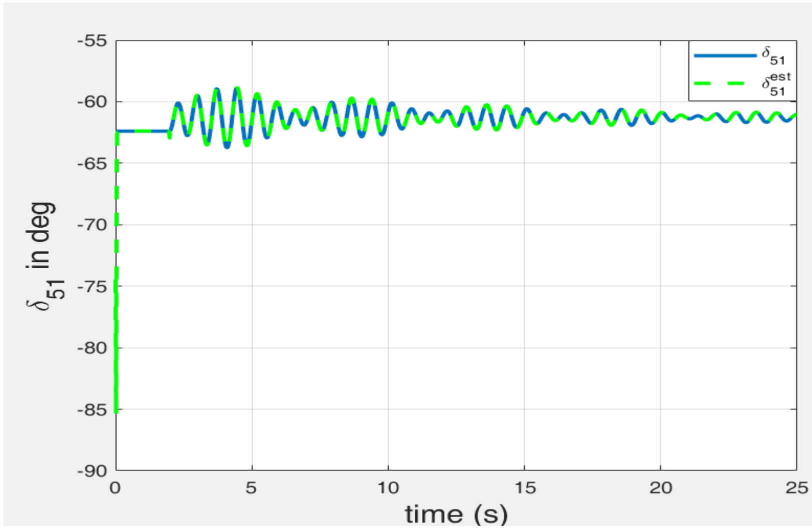

Figure 4.7: δ_{5-1} estimated by EKF and theoretical value

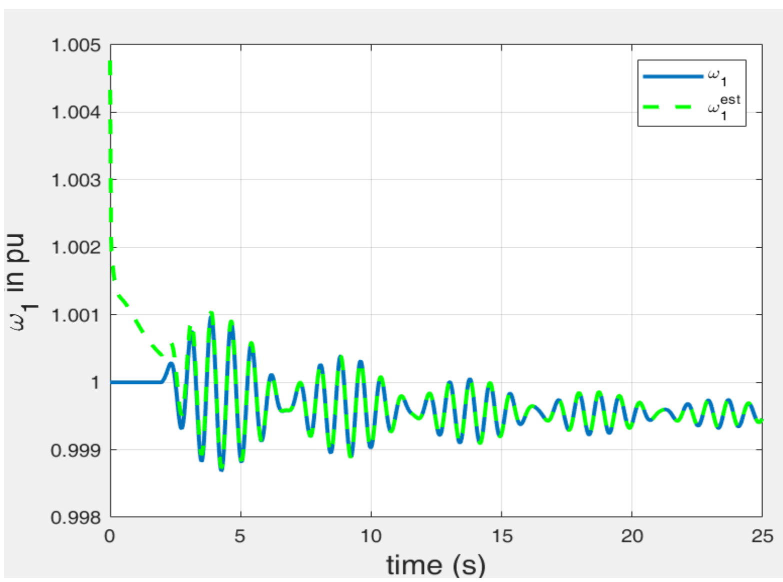

Figure 4.8: ω_1 estimated by EKF and theoretical value

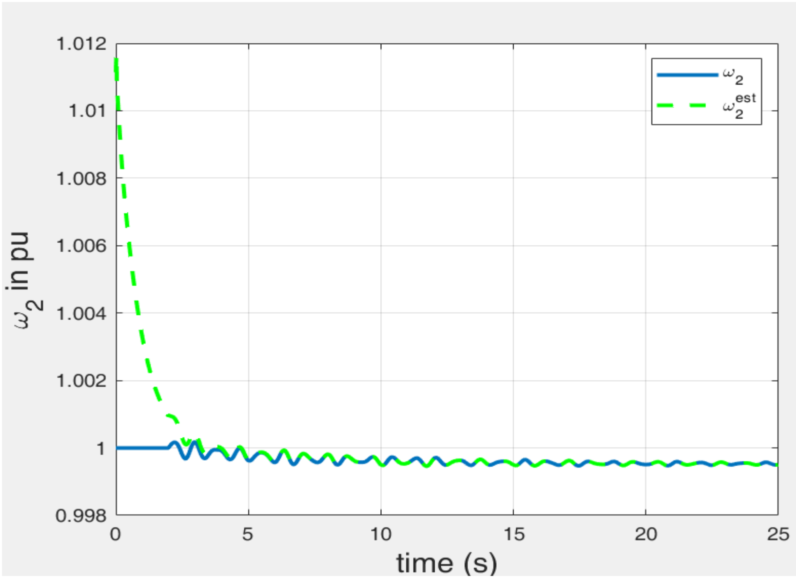

Figure 4.9: ω_2 estimated by EKF and theoretical value

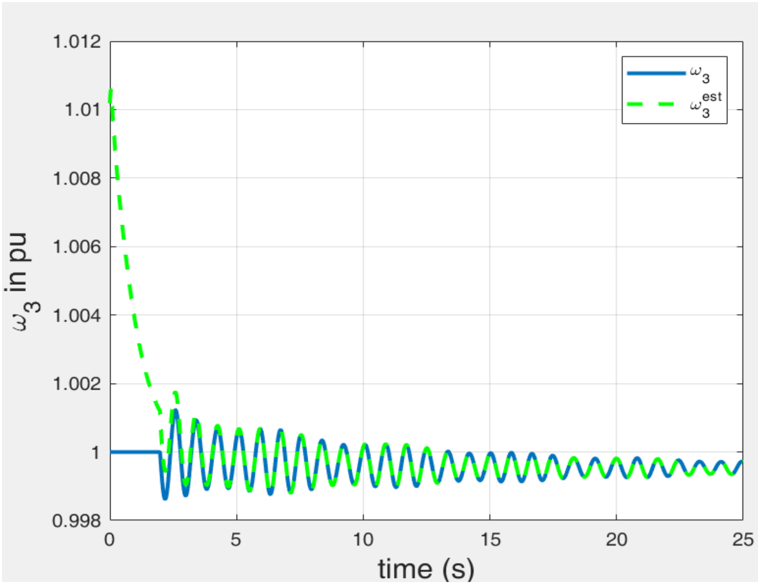

Figure 4.10: ω_3 estimated by EKF and theoretical value

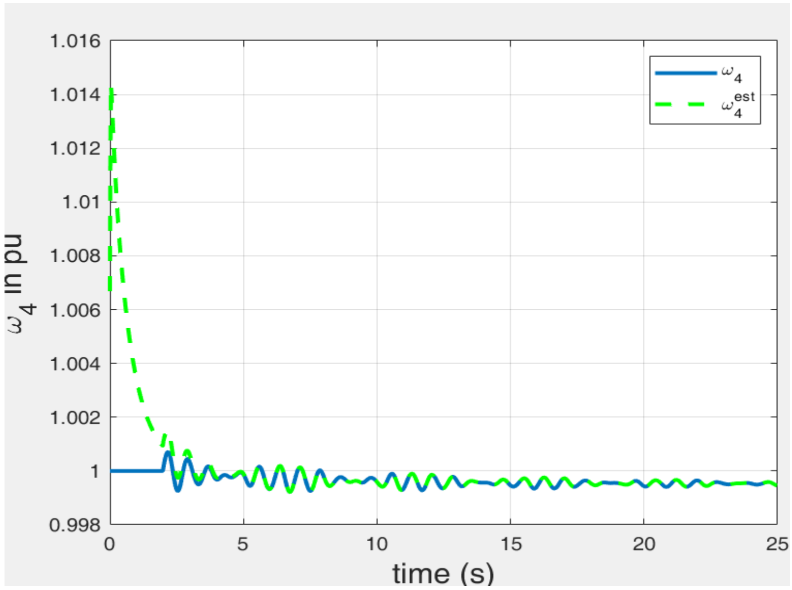

Figure 4.11: ω_4 estimated by EKF and theoretical value

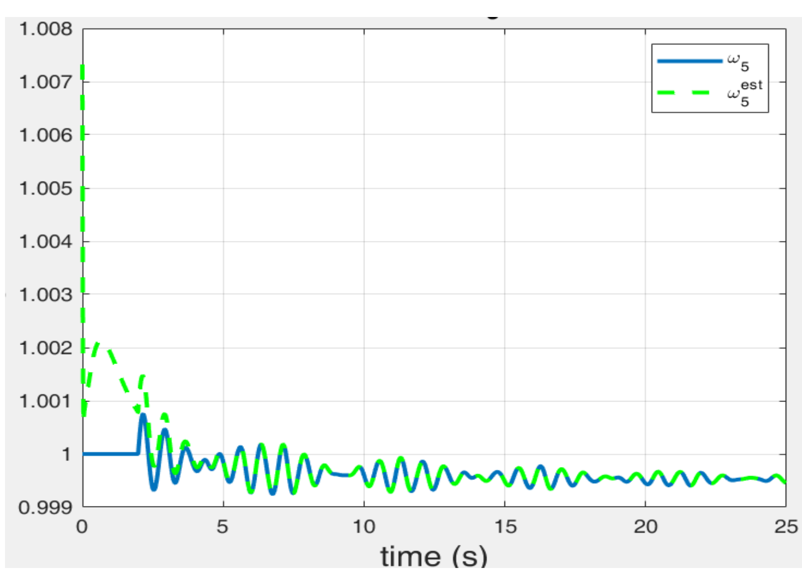

Figure 4.12: ω_5 estimated by EKF and theoretical value

4.5 Conclusion:

Monitoring and control of the electrical power network necessitates the dynamic state estimation. In this dissertation dynamic variables of multi machine IEEE 14 bus, 5 generator system is estimated using EKF method. The transient condition is considered and the simulations are performed in MATLAB. The estimated dynamic variables under transient conditions obtained by applying the EKF algorithm and the dynamic variables calculated with the Fourth order Runge Kutta method are compared to depict the efficacy of the algorithm. The performance indices (ε_{ω},ε_{δ}) are also calculated which indicate the accuracy of the EKF method employed to the test system.

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