A Survey on Real Time State Estimation for Optimal Placement of Phasor Measurement Units in Power Systems using Kalman Filter

Gazala Rashid[1] Vaibhav Shukla[2] Munmun[3] Kripal Singh Doad[4]
[4]Assistant Professor
[1,2,3,4]Lovely Professional University, Phagwara, Punjab, India

Abstract— The traditional methods of security assessment using offline data and SCADA data have become inconsistent for real time operations. The latest and propelled strategy in electric power system used for security assessment is "synchrophasor" measurement technique. The device called Phasor measurement unit (PMU) provides the time stamped data for proper monitoring, control and protection of the power system. PMU measures positive sequence voltage and current time synchronized to within a microsecond. The time synchronization of data is done with the help of timing signals from Global Positioning System (GPS). However, Phasor measurements units cannot be placed on every bus in a network mainly because of economical constraints. In this paper we provide a literature survey of determining the minimum number of Phasor measurement units to be placed in a given network so that the system becomes observable.

Key words: Pharos measurement unit, Global Positioning System, synchrophasors, kalman filter, Remote terminal unit, SCADA, mean, variance, covariance

I. INTRODUCTION

Secure operation of the power systems obliges the close checking of working conditions of the system. The measurements got from various substations are utilized as a part of control focuses to give an assessment to all metered, unmetered electrical amounts and system parameters of the power systems recognize and channel out estimation and topology slips. Up to this point, the accessible measurements were given by SCADA. The use of Global Positioning system (GPS) has prompted the advancement of PMUs. Phasor Measurement Units are the measuring devices that give to a great degree precise positive sequence time labelled measurements. The Phasor measurement Unit advancement was bolstered at Virginia Tech by different subsidizing organizations throughout the years. Phasor measurement innovation (for application in the power industry) was created close to the end of 1980s. At present PMUs are the most refined time synchronized apparatus accessible to control designers and power system operators for wide area applications. Positive sequence voltages of a system constitute the state vector of a power system and it is of major significance in all power system investigations. The principle paper that distinguishes the significance of positive sequence voltage and current Phasor measurements was published in 1983 and this last paper can be seen as the beginning stage of the synchronized Phasor estimation innovation.

II. NEED OF PMU

Phasor Measurement Units evolved out of the improvement of "symmetrical component distance relay". All the three phase currents and voltages are utilized so that positive sequence estimation can be done.

Rather than a relay, a Phasor measurement unit can have currents in a few feeders beginning in a substation and voltages fitting in with different buses in the substation. For the best possible and secure operation of the power system it is important to screen the working states of the system closely. The data of the diverse parameters from distinctive substations got at the control centre gives the estimation of all figured and non computed quantities or system parameters of the frame work too distinguishes and channel out the errors in the estimation and innovation. The traditional estimation methods measure just the voltage magnitude of the buses yet they cannot measure the phase angle specifically. SCADA systems give the continuous measurements got through Remote Terminal Unit (RTU) introduced at substations which incorporates active and reactive power flows and the magnitude of bus voltages. Thus, with the evolution of Phasor Measurement Units, they are utilized for checking, security and control of power system. Phasor Measurement units are connected with relays so they can consequently rectify the errors happened in the system.

III. LITERATURE SURVEY

1) PMUs can't be placed at every node of the network because of their high cost and limited bandwidth of the communication channel. Thus, it is necessary to find the location as well as minimum number of PMUs required in a system. So a number of stochastic (SA, GA, NDSGA, TS) and deterministic (ILP, Quadratic Programming) search algorithms have been proposed. These algorithms provide a number of optimal solutions and these solutions are refined by using various optimization techniques such as Maximum Measurement Redundancy (MMR) criteria. Though by using MMR the number of PMUs gets reduced but the solution obtained is not unique. Hence, the authors proposed the steady state kalman filter state estimation error covariance to get the optimal solution. The paper also considers the Random Component Outages (RCO) which may alter the optimality of the solution. In this paper Integer Linear Programming (ILP) method has been used to solve the optimal placement problem (OPP) of PMU. In addition to this, EEC (Estimate Error Covariance) has been minimized. In steady state estimation the location of PMUS is chosen in such a way that the expected value of the norm of EEC is minimized. However in dynamic state estimation (DSE) the expected value is time varying in nature. Hence for DSE the asymptotic value is to be calculated by using a sequence of upper and lower bounds. By using the bounding sequences an algorithm for optimal solution is formulated. The calculations for optimization are done using Monte Carlo methods.
2) Kalman Filter came into existence in 1960 R.E. Kalman published a paper in which he provided

solution of linear filtering problem with discrete data. Kalman Filter is a set of mathematical equations that minimizes the mean of the squared error to estimate the state of the process. The mathematical equations include the difference equation of the process and the equation for measurement. The deviation between the actual measurement and the predicted value is called as residual. If the residual is zero then the actual measurement and the predicted values are equal. The noise present in the process is called as process noise and its covariance is called as process noise covariance represented by "Q". The noise present in measurement is called as measurement noise and its covariance is called as measurement noise covariance represented by "R". When the measurement error covariance "R" approaches to zero the actual measurements are believed to be more accurate as compared to the predicted values. Kalman Filter is considered to be a predictor-corrector algorithm having two sets of equations –Predictor equations and corrector equations. In Kalman Filter the state of a process is estimated by using feedback loop. The measurement noise acts as a feedback. The predictor equations are the time update equations which update the current state of the estimate for the next step. The corrector equations are the measurement update equations which act as feedback and provide the improved estimate using Kalman gain. The steps involved in Kalman filter algorithm are as under:

- Calculate the Kalman Gain.
- Find the a posteriori state estimate using the measured values
- Calculate a posteriori error covariance estimate.

For non-liner filtering problems Extended Kalman Filter (EKF) is used. In EKF the current estimate and the measurements are linearized using Taylor series and partial derivative method.

3) The Remote Terminal Units (RTU) placed at substation terminals measure the following quantities:

- Line power flow
- Bus power injection
- Voltage magnitude

The PMUs provide the two additional measurements – Voltage Phasor and current Phasor measurements. The bus voltage magnitudes and phase angles are taken as state variables in steady state estimation while in dynamic state estimation the state variables are generator rotor angle and speed. For the optimal placement problem of PMU the various algorithms that have been formulated so far provide a more than one solution for the same minimum number of PMUs. Hence the problem is to choose the better solution among them. This paper solves the problem by calculating the Estimate Error Covariance (EEC). The solution with lower EEC is chosen as the best solution. Integer Linear Programming algorithm is used to solve the OPP problem and the possible solutions for minimum PMUs are obtained. The error estimate covariance is obtained from state space model. The state space model consists of Process model and the measurement model. In process model A and Q are calculated using rotor angle and speed as state variables where Q is the process noise covariance and A is a matrix that gives the relationship between the state at time step (k-1) and the current state at time step k. In measurement model H and R are to be calculated where H is a matrix that relates state to the measurement and R is the measurement noise covariance. The measurement noise covariance is found experimentally by testing PMUs. After calculating A, Q, H and R, the Hamilton matrix is found. With the help of eigenvectors of Hamilton matrix, EEC is calculated.

4) In conventional method of state estimation the bus Phasor voltages are estimated using real and reactive power as the measurements. Hence the relation between the states and the measurement is non linear. Since PMU measures the bus Phasor voltage and the Phasor current, the measurement and state relationship becomes linear. In power system modelling, PMU measurements and zero injection bus measurements are to be considered. Using integer linear programming approach different optimal solutions for same number of PMUs are obtained. Each of the optimal solutions will be having different estimate uncertainty. Hence the solution with lower estimate error covariance is chosen as the better solution. The certainty (information) from each configuration is obtained. The maximum, minimum and the mean of certainties is calculated to choose the better solution.

5) The type and the location of the fault are determined using Kalman filter and adaptive Kalman filter. A complete procedure and algorithm for both the processes is elaborated and implemented for digital distance protection. The results of kalman filtering and adaptive Kalman filtering processes are compared. The comparison of the two processes show that the estimates converge faster to the exact values in adaptive kalman filtering and hence the apparent impedance and fault calculations zero in faster than the kalman filtering process. In addition to this protection algorithms are formulated which are tested on Zoran Vector Signal Processor Simulator (VSPS).

6) The consideration of nonlinearities in developing dynamic models of a physical system has become an important factor. This paper provides complete solution for non linear tracking problems using optimal and suboptimal Bayesian algorithms. The optimal algorithms include Kalman filter and Grid- based methods. There are certain assumptions made in the optimal algorithms. The solution provided by the Kalman filter is tractable if the system holds such assumptions. However, most of the systems don't hold such assumptions and hence the solution becomes intractable. For such situations suboptimal algorithms have been proposed. In suboptimal algorithms, three types of nonlinear Bayesian filters are considered viz; extended kalman filter (EKF), approximate grid-based methods and particle filters. This paper mainly focuses on particle filters. Particle filters are basically sequential Monte-Carlo Methods. In such filters density is approximated directly as finite number of samples. A variety of particle filters are discussed in this paper. The choice of a filter for a particular application depends on the importance density.

7) The dynamic state estimation of a power system by extended kalman filter uses synchronous machine rotor angle and speed as state variables. The extended

kalman filter is used when the input data is measured easily. In some cases such as brushless exciters the input data like field voltage or mechanical torque cannot be measured easily. For such situations extended kalman filter with unknown inputs (EKF-UI) is proposed to estimate the states as well as the unknown inputs. Also the simulation results for both the approaches are compared.

8) Kalman Filter is a state estimator that is used for linear dynamic systems with Gaussian noise. For nonlinear dynamic systems several modifications of kalman filter are proposed for state estimation of the system. In this paper the various approaches used for state estimation have been classified on the type of system constraints. For linear constraints the various approaches used are estimate projection, gain projection, model reduction, system projection, probability density function truncation etc. The approaches used for the system with nonlinear constraints include second order expansion of constraints, unscented kalman filter, smoothly constrained kalman filter, particle filters etc. For state estimation of the system several approaches can be combined together to get the better performance.
9) In power systems the measurements obtained from the communication network may contain false or bad data. Also due to inter-area oscillations between the generators these measurements become less trust worthy. A distributed kalman filtering approach has been proposed for such problems so as to avoid measurements from less trusted PMUs. In this paper two modified trust based algorithms are proposed. In first algorithm the trust is utilized to evaluate estimation errors in terms of measurement noise and observation. In second algorithm trust is interpreted in terms of security. For large noises in the system and bad data these trust based algorithms give better results when compared to the original distributed kalman filter.
10) The optimal placement problem is solved by integer linear programming method. The measurements obtained from each PMU are limited by some communication constraints. In this paper these communication constraints are considered as measurements limitations. Also line outages and loss of measurements are included in the main model which makes the method more flexible. The proposed method is suitable for the large-scale power system applications due to its low execution time.

IV. Conclusion

Phasor measurement unit is an excellent indicator of system stress as it provides information about the bus angle voltage. However, such devices cannot be installed at each bus in the system due to its cost factor. A number of optimization techniques have been proposed to solve the problem. This paper provides a literature survey of OPP of PMUs. The paper mainly focuses on kalman filtering technique. The kalman filter algorithm converges quickly to the exact values as compared to other methods which suffer from heavy computational burden.

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