PMU BASED DYNAMIC STATE ESTIMATION TECHNIQUE

MAYURDHVAJSINH P. GOHIL
Electrical Power System
Dr. Jivraj Mehta Institute of Tehnology
Anand, Gujarat, India
mayur.afs@gmail.com

VANDIT PANDYA
Electrical Power System
ME(PURSUING)
Vanditpandya2000@yahoo.com

Abstract-This paper presents the Boolean algebra into state estimation to covenant with topological position. It consents to power system operators to express consistent state estimation in a intellect that network topology is recognized while estimation is evaluated. State Estimation customs one of the primary EMS functions at the regulator epicenter. Precision of the state estimation hang on the accuracy of the measurements used. Hence, it is highly indispensable to use accurate measuring devices. Phasor Measurement Units (PMU), with their inherent high accuracy and the unique ability to measure the voltage angles, offers a great improvement in the overall accuracy of the state estimation. Few techniques have been proposed in the literature for using PMUs in static state estimation. It is also important to use PMU data in to Dynamic State Estimation (DSE), which envisage the state of the system one step ahead.

Keywords— energy management system (EMS),phasor measurement unit (PMU), Dynamic State Estimation (DSE), supervisory control and data acquisition (SCADA)

I. INTRODUCTION

The studies on state estimation have been classified into the following:

a) development of fast algorithms
b) bad data detection and suppression
c) hierarchical state estimation
d) observability analysis
e) optimal meter allocation
J) topology identification

In this section, the concept of topology identification is described. This paper introduces This paper focuses on item to make state estimation more robust. Topology identification is to main concern in power system operators. It aims to examine how the transmission line is connected to the nodes. Reliable evaluation of topology identification helps power system operators to understand power system conditions appropriately. The importance of topology identification has been revaluated after the blackout in the North America, August 2003. As a result, more sophisticated methods are required to handle network topology identification from a standpoint of robustness and computational efficiency.

State estimation is a computationally intense process. Hence, it is run either at fixed intervals of time or once it is found that the power system has sufficiently changed from its PMU and normal SCADA measurements in to the state estimation algorithms. This paper presents a novel technique to include PMU measurements in to a dynamic state estimation technique and study its effects on the estimation process. In the technique presented here, incorporation of PMU based voltage magnitude and voltage angular measurements in to the DSE has been studied. With the power system being expanded, especially in the developing countries, more accurate monitoring and control of the system becomes essential, necessitating more PMUs to be installed. Hence, PMU based dynamic state estimation becomes very important in the modern day energy management systems.

II. TOPOLOGY IDENTIFICATION

Boolean algebra into power system state estimation problem to carry out state estimation in consideration of network topology. This paper aims to evaluate network topology and state variables at the same time. In that sense, power system state estimation is extended to deal with network topology. Network topology may be divided into branch and node topology.

A. Branch Topology Identification

Branch topology identification is to judge whether a doubtful line exists or not or estimate where a line is Connected to. Fig.1shows the concept of branch

$$\sum_{i \in I_l} \alpha_l^i \leq 1 \quad (\forall l \in L)$$

…..(1)

Where, I: set of Node i for Branch l
L: set of doubtful Branch l

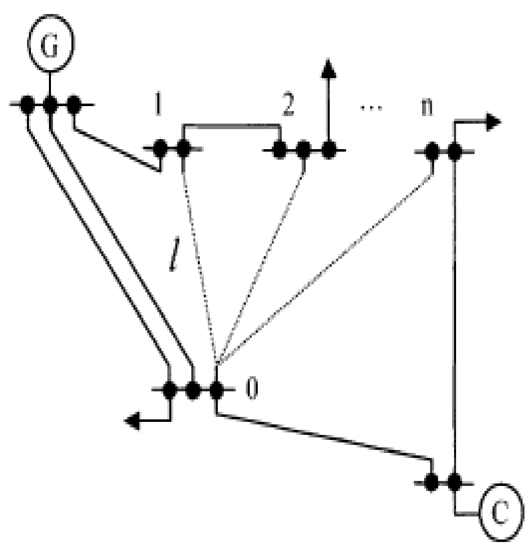

Fig. 1 Concept of branch topology identification.

Now, let us consider state estimation in consideration of branch topology. Measurement matrix H in may be rewritten as

$$H = H_0 + \sum_{l \in L} \sum_{i \in I_l} \alpha_l^i H_l^i$$

…..(2)

Where,

Ho : measurement matrix without doubtful topology

H_i^l : modified measurement matrix in consideration of the relationship between Branch l and Node i.

Thus, state estimation in consideration of branch

….(4)

topology identification, where Node 0 implies the starting point of Branch l and Branch l looks for the ending point. Now, suppose that Node i (i =1…,n) is a candidate of the ending point. To model the relationship between Branch l and Node i, the following Boolean variable is introduced:

Branch I from Node 0 selects only one ending node. The constraint may be expressed as,

Since Branch l should be connected to only one node, the Boolean variable β_{il} has the following constraint:

$$\sum_{i \in I_k} \beta_l^i = 1 \quad (\forall l \in L_k)$$

…(3)

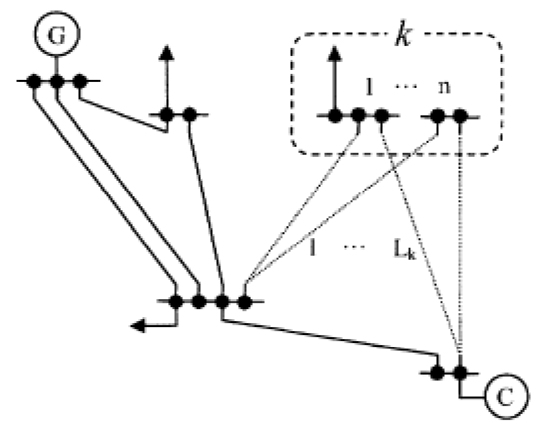

Fig.2 Concept of node topology identification.

Where,

Ik: set of decomposed Node i at Substation k

Lk: set of Branch I connected to Substation k

The measurement matrix H may be rewritten by the Boolean variable.

$$H = H_0 + \sum_{k \in K} \sum_{l \in L_k} \sum_{i \in I_k} \beta_l^i H_l^i$$

$$\begin{cases} 1: \text{ Branch } l \text{ is connected to Node } i. \\ 0: \text{ Branch } l \text{ is not connected to Node } i. \end{cases}$$

topology is carried out to identify whether Branch l exists and where the ending node is.

B. Node Topology Identification

Node topology identification is to separate a node at a substation. There is possibility that a doubtful substation should be divided into some decomposed nodes. As shown in Fig. 2, Substation k is separated into n decomposed nodes. The nodes are connected to other nodes by Lk branches. Boolean variable, β_i^l is introduced into the problem above.

$$\beta_i^l = \begin{cases} 1: \text{ Branch } l \text{ is connected to Node } i. \\ 0: \text{ Branch } l \text{ is not connected to Node } i. \end{cases} \quad \text{.....(5)}$$

Where,

K: set of doubtful Substation k

To model the state of the decomposed node at substation, the following Boolean variable is used:

$$\lambda_i^k = \begin{cases} 1: \text{ Node } i \text{ has no connection with others.} \\ 0: \text{ Node } i \text{ has connection with others.} \end{cases} \quad \text{....(6)}$$

The relationship may be written as:

Suppose that the reference angle of $\theta_{ref} = 0$ is available ifNode i has no connection with others.

$$\lambda_i^k = 1 \quad \Rightarrow \quad \theta_i^k = \theta_{ref} \quad \text{.....(7)}$$

Where,

θ_{ref} : voltage angle of Node i at Substation k

Therefore, the nodal state at the substation is identified by optimizing node topology.

III. PHASOR MEASUREMENT UNITS

In the 1980s, a device called the Synchronous Component Distance Relay (SCDR) was developed for transmission line protection. This device had the ability to calculate the synchronous components of the voltage and current on the transmission lines. Since the state vector of a power system consists of positive sequence voltage vectors at all the buses of a power system, this device clearly had the ability to directly measure the state vector. Though the device was developed primarily for protection applications, its ability to directly measure the voltage phasors paved the way for its usage in state estimation and this led to the eventual development of Phasor Measurement Units (PMU). The PMUs main advantage comes from the fact that, probablyfor the first time we can have synchronized measurements of parameters across the power system. The PMUs use the GPS system to synchronize the measurements. The accuracy of the synchronisation can be as low as 1µs. The PMUs receive the one pulse per second GPS signal, along with the time tag, which is used as an initiation for the measuring the positive sequence voltages and currents. This data is in turn transmitted to the control center, through suitable communication channels for monitoring and control applications . As PMUs can measure the phasors with extremely high accuracy which are also synchronized, their addition in to the state estimators, even if in a few locations, should improve the performance of the state estimation process considerably.

IV. PHASOR MEASUREMENTS IN STATIC STATE ESTIMATION:

Before venturing in to dealing PMUs in dynamic state estimation, it's important to take a look at some of the conclusions obtained from the experience of including PMUs in static state estimation. These conclusions drawn from incorporating PMUs in static state estimation have been taken in to account while developing algorithms for incorporating PMU measurements in DSE. As we know, PMUs may not be installed at all the location of a power system, the estimation algorithms have to process a mixture of both the PMU measurements and the normal SCADA measurements. There are two different schools of thought regarding the way of incorporating the PMU measurements in to state estimation. The first method, called the Direct Substitution technique, suggests that the PMU data are far superior to the normal SCADA data and hence have to be collected and used separately from the SCADA data. This method considers that the PMU based voltage magnitude and angular measurements at a particular bus, to be equal to the state at that particular bus and the estimation process is carried out only for other buses where PMUs are not installed. The other school of thought suggests that, though the PMU data are different from the SCADA data, they can nevertheless be used along with SCADA data in the estimation process, albeit with higher weights. The first method uses the voltage magnitude and angle measuring ability of the PMUs fully. But the disadvantage of this method is that the high accuracy of the PMU measurements is not contributing to the estimation process. But in the second method, the high accuracy of the voltage and angular measurements of PMU participate in the estimation process and hence help in reducing the errors in estimation due to other less accurate measurements. In the second method, the accuracy can further be improved by replacing the voltage magnitude and angular estimates corresponding to the PMU measurements by PMU measurements themselves, once the state estimation is complete. This method is found to produce lesser error in the final state estimates.

Some of the conclusions obtained from the PMU based static state estimation techniques are

1. The angular measurements play the same role in active measurement residuals as the voltage measurement plays in the reactive measurement residuals.

2. The introduction of highly accurate angular measurements increases the convergence speed especially in larger systems.

3. State estimation results are more sensitive to angular measurement errors than to errors in power flow measurements.

4. Of the two estimation techniques presented, the second method of incorporating PMU measurements with larger weights is preferable as it has better accuracy.

These conclusions form the basis of our model for incorporating the phasor measurements in dynamic state estimation.

V. DYNAMIC STATE ESTIMATION

Power system is a dynamic system, and hence changes continuously but slowly. The static state estimators, failed to model this quasi-static behavior of the power system. The DSE techniques have a mathematical model for the time behavior of the power system and hence deliver more realistic estimates. DSE uses the present (and some times previous) state of the power system along with the knowledge of the system‟s physical model, to predict the state vector for the next time instant. Once the new measurements at the next instant of time arrive, the predicted values are filtered to obtain a more accurate estimate of the states. This prediction feature of the DSE provides vital advantages in system operation, control, and decision-making. It allows the operator more time to act in cases of emergency, helps in detection of anomalies, bad data etc. The following are the main steps followed in the DSE procedure:

1. Mathematical modeling: The first step in DSE is to identify a suitable mathematical model for the time behavior of the power system.

2.Parameter Identification: This step involves the calculation of the parameters that make up the mathematical model describing the behavior of the power system

3.State Prediction: This step, predicts the state vector at the instant of time (say „k+1‟), from the knowledge of state vector at the present instant (say „k‟) and the mathematical model.

4.State Filtering: Once the measurements are obtained for the instant „k+1‟, the predicted state vector is simply updated to obtain a more accurate estimate of the state of the system.

At the end of these three steps, the DSE gives an updated estimated state vector of the power system, which in turn will be used by other EMS functions.

Leite Da Silva et al has presented a technique, which uses Holt‟s double exponential smoothing technique for prediction and Extended Kalman Filter (EKF), for the filtering process. This paper uses the above DSE technique for incorporating phasor measurements. The mathematical model for the time behavior of the system is given by:

$$x_{k+1} = F_k x_k + G_k + w_k \quad \text{......(8)}$$

Where xk+1 and xk represent the state vector at instants „k+1‟ and „k‟ respectively, Fk is the function representing the state transition between two instants of time, Gk is associated with the trend behavior of the state trajectory and wk is the white Gaussian noise with zero mean and covariance Q. The measurement model is given by:

$$Z = Hx + v \quad \text{.......(9)}$$

Where ***Z*** is the measurement vector, **x** is the state vector, ***H*** is the Jacobian of the nonlinear function relating the state vector and the measurements and ***v*** is the noise in measurements with a standard deviation of ***R***. Here ***R*** is of the form:

$$R = \begin{pmatrix} \sigma^{-2} & 0 \\ 0 & \sigma_{PMU}^{-2} \end{pmatrix} \quad \text{Where } \sigma^{-2} << \sigma_{PMU}^{-2}$$

........(10)

Where „σ' is the standard deviation of the normal SCADA measurements and „σ_{PMU}" is the standard deviation of the PMU measurements.

The parameters, Fk and Gk are calculated using the Holt"s double exponential smoothing method and the predicted state vector is obtained by the following equation:

$$\bar{x}_{k+1} = F_k \hat{x}_k + G_k$$ **..........(11)**

Where, x is the predicted value at instant „k+1". The covariance of predicted values at instant „k+1" is given by:

$$N_{k+1} = F_k P_k F_k^T + Q_k$$ **.........(12)**

Where, „Pk" is the covariance of the estimate at instant „k".

This predicted estimates, will then be used to predict the measurements at the next instant of time. When the measurements at the k+1 instant arrive, the predicted state vector x has to be updated, to obtain the filtered estimates.

The optimization function here would be, to minimize the difference between predicted measurements and the actual measurements at the „k+1"th instant. The second factor to minimize is the difference between the predicted and the actual state vector. Hence the optimization function is given by:

$$J(x) = [Z - h(\bar{x})]^T R^{-1} [Z - h(\bar{x})] + [x - \bar{x}]^T N^{-1} [x - \bar{x}]$$

........(13)

The Extended Kalman Filter (EKF) technique is used for optimizing the above equation and the final equation for the filtering step can be written as:

$$\hat{x}_{k+1} = \bar{x}_{k+1} + K_{k+1}[Z_{k+1} - h(\bar{x}_{k+1})]$$

$$\text{Where } K_{k+1} = \Sigma H^T R^{-1} = [H^T R^{-1} H + N^{-1}]^{-1} H^T R^{-1}$$

.....(14)

K is called Gain matrix.

At the end of these steps, the DSE gives an updated estimated state vector of the power system, which can in turn be used by other EMS functions for their operation.

VI. PMUS IN DYNAMIC STATE ESTIMATION

From the experience of incorporating PMUs in static state estimation, it can be concluded that, PMUs by and large increase the performance of the state estimation. Keeping in mind the conclusion drawn from the PMU based static state estimators we propose a PMU based DSE technique. With PMUs we can have much more accurate filtered states, resulting in more accurate predicted states for the next instant of time. Hence, the operator will have much more reliable data for performing security analysis and taking control decisions. In these days of expanding power grids and the system being pushed towards its limits for maximum utilization, any improvement in accuracy of the prediction and accuracy of estimated state variables can be extremely useful.

The DSE model used here is as described in the previous section. In this paper incorporation of PMU based voltage magnitude and voltage angular measurements in to the DSE will be studied. Some of the observations from the PMU based static state estimation techniques, which can be useful in modeling the PMU based dynamic state estimation are:

1. The system will consist of a mixture of both PMU measurements and normal SCADA measurements.
2. The PMU measurements will be used in the state estimation along with the SCADA measurements, albeit with higher weights.
3. Once the filtered estimates are obtained, voltage magnitude and angular estimates corresponding to the PMU measurements are replaced by the PMU based voltage and angular measurements themselves, to increase the accuracy.
4. The behavior of the DSE will be studied by observing its response for varying weights of the PMU measurements.

The PMU based DSE technique presented in this paper, has been implemented and tested on a 5-bus system. The system dynamics is simulated through change in the injections at various buses. The PMU will be introduced at each bus, one at a time, and the DSE program is run for each such placement of PMU. At each location, the weight values given to the PMU measurements are varied and the behavior of the estimation process studied. Once the placement of PMU at all the buses has been completed, a combination of PMUs at 2 buses of the system will be introduced. These combinations are then repeated for various weight values of the PMU based measurements. The accuracy of the estimates for various combinations of the above experiments will give a fair idea about the performance of the PMU based DSE technique that has been implemented.

VII. CONCLUSIONS

This paper has proposed a new state estimation method for network topology identification in power systems. In this paper, Boolean variables were introduced to express network topology for branches and nodes so that the formulation of state estimation is expressed by a mixed integer problem. Namely, network topology is expressed in binary number and nodal voltage states are represented in continuous one.

This paper also proposed that PMUs are extremely accurate measuring devices, with the ability to directly measure the voltage and current phasors. These high accuracy measurements of the PMUs may not be warranted, as many state estimation techniques are not equipped for handling them. Many researchers have proposed techniques to handle PMU data in static state estimation. An attempt has been made in this paper to present a PMU based dynamic state estimation technique. Some of the conclusions obtained by other researchers from PMU based static state estimation techniques have also been considered to improve the efficiency of the PMU based DSE. Accordingly, the technique uses the phasor measurements in the estimation process along with normal SCADA data, but with higher weights.

With the power sector being deregulated and the utilities trying to monitor the system as accurately as possible, for more efficient operation, the usage of PMUs is bound to increase. From this point of view, PMU based dynamic state estimators are of extreme importance in the modern day EMS.

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