# New method of state estimation based on PMU

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## Abstract

**According to the current SCADA/PMU mixed measuring main SCADA data-oriented hybrid State estimation. This paper proposes a method takes the PMU data is given priority to, After measurement with of the transformed SCADA data and PMU pseudo measuring data can be insufficient to PMU observation point data added, To reach the PMU system of measuring the considerable, Increasing state estimation data redundancy, Amended iterative equation of weights.The simulation results show that the method under the condition of less configuration PMU has a faster convergence speed, and, compared with the traditional state estimation method, along with the increase in data PMU, convergence speed can be improved, on the calculation precision, also can and all nodes are PMU after the state estimation of basic consistent.**

## Keywords

**Supervisory control and data acquisition(SCADA); phasor measurements units(PMU); state estimation; Mixed measurements system.**

## 1. Introduction

Power system state estimation is one important part of the energy management system (EMS). In recent years, domestic and foreign experts, institutions of phasor measurements units (PMU) based on EMS research has made great progress, formulate the corresponding technical specification and has been equipped in power systems[1-5]. According to incomplete statistics, more than 1000 sets of phasor measurements units are invested in power grid operation in China[6]. As the phase angle information is difficult to obtain, in recent time most of power system dispatching center is supported by SCADA system, iteration method are used for nonlinear equations of voltage phase angle. With all nodes equipped with PMU, the magnitude and phase angle of each node can be measured directly in the system voltage. Obviously, at this time the state estimation equation could be solved without iteration. This is proposed by Dr A.G. Phadke when he explored the PMU application in state estimation[7].But it cannot achieve all configuration of PMU due to the following reasons.

(1) The cost of PMU can be accepted, taking Heilongjiang Province for example, it has more than 200 nodes, each PMU device is about 20000 yuan, but it requires more money to build the completely observable WAMS system, and give up the complete SCADA system which did before, it would cause enormous waste, which does not comply with the conservation-oriented society requirements.

(2) The current SCADA system technology is already mature with considerable operational experience, but it will take a great technical risk to use the WAMS system replace the SCADA system completely.

(3) Comparing with existing power communication facilities, WAMS system will generate huge amounts of milliseconds data, combined with the WAMS data due to communication delays technology, measurement and delivery system that appears accidental error and other factors inevitably produce some errors, it can be reduced by the data processing method. But the attendant is a greater amount of data, these massive data exceed the current computer processing capability[8].

Therefore, the complete PMU configuration is not suitable for the current power system state estimation, so the combination of PMU and SCADA data together into the state estimation is particularly important. In this kind of method, adding PMU in SCADA system voltage phasor measurement data is the most direct way. However, the current phasors measured by PMU did not get the effective use[8]. On the basis of the literature [8] and [9], the current phasor in the system is transformed into active and reactive power, increasing the redundancy of state estimation, thus improve the precision of state estimation. The Literature [12][13][14][15] are all based on SCADA system approach to system state estimation. And the trend with the capital accumulation of technology and progress, the number of PMU will be increase. Based on the above, this paper offer a state estimation method based on PMU, using the measurement transformation, making the system achieve significant, then operating the state estimation.

## 2. Linear measurement system model based on PMU measurements

### 2.1 Traditional measuring state estimation method

In power system, network connection,branch parameters are given and in the condition of measurement system,the nonlinear measurement equation can be rewritten as:

$$z = h(x) + v \tag{1}$$

After giving the measurement vector $z$ ,state estimation vector $\hat{x}$ is the value of x that make the objective function J (x) reaches minimum.

$$J(x) = [z - h(x)]^T R^{-1} [z - h(x)] \tag{2}$$

Wherein z is a vector of quantity measured, $h(x)$ is a vector of quantity measured function, $x = e + jf$ is the state vector, v is the measurement error. $R^{-1}$ is measurement system weight matrix, after linearization of x.

$$h(x) \approx h(x_0) + H(x_0)\Delta x \tag{3}$$

$H(x)$ is the Jacobian matrix which is a $m \times n$ rank measurement vector. according to the type (2) and (3)

$$J(x) = [\Delta z - H(x_0)\Delta x]^T R^{-1} [\Delta z - H(x_0)\Delta x] \tag{4}$$

Analysis of the formula:

$$(H^T R^{-1} H)\Delta x = H^T R^{-1} (z - h(x)) \tag{5}$$

$H(x_0) = \frac{\partial h(x)}{\partial x}|_{x=x_0}$ is the quantity measured Jacobian matrix, $H^T R^{-1} H$ is the state estimated information matrix.

### 2.2 The equivalent measurement transformation

Assuming the nodal injection power measurement is $P_i, Q_i$ ,the branch current amplitude measurement is $P_{ij}, Q_{ij}$ ,branch current amplitude measuremen is $I_{ij}$ ,node injection electrical measurement is $I_i$ , $e_i$, $f_i$ are I side of the node voltage real part and imaginary part of node voltage. After equivalent measurement transformation:

$$I_i = \frac{P_i e_i + Q_i f_i}{e_i^2 + f_i^2} + j\frac{P_i f_i - Q_i e_i}{e_i^2 + f_i^2}, \tag{6}$$

$$I_{ij} = \frac{P_{ij} e_i + Q_{ij} f_i}{e_i^2 + f_i^2} + j\frac{P_{ij} f_i - Q_{ij} e_i}{e_i^2 + f_i^2}, \tag{7}$$

The formula (6), (7) show that the equivalent branch current phasor measurements, equivalent nodal current phasor measurements is the function of state variable e, f ,After iteration must use recalculated value of state variables,according to the law of error transfer in indirect measurement, measurement variance is $\delta_y^2=\sum_{m=1}^{n}[(\frac{\partial F}{\partial x_k})^2\delta_{xm}^2]$ ,The indirect measurement $y=F(x_1,x_2,\cdots x_n)$ , $x_1,x_2,\cdots x_n$ is direct measurement and obey the normal distribution of random variables.When active, reactive power measurement variance approximately equal, then the measurement variance can be approximately equal the node power measurement $P_i,Q_i$ or the variance of branch power measurement $P_{ij},Q_{ij}$ , the node active and reactive power measurement respectively $R_p^{-1}=\delta_p^{-2}$ and $R_q^{-1}=\delta_p^{-2}$ , and equal to real part and imaginary part, the weight of the corresponding current node can be obtained

$$\frac{(e_i^2+f_i^2)^2}{e_i^2R_p+f_i^2R_q} \tag{8}$$

Branch current weight in the same way.

## 3. Analysis to the observability of system based on PMU

Considerable power systems [10]consist of the systems quantity measurement, the total class and the distribution of the current state of the system can be solved (including the node voltage phasor, system of active and reactive power, etc.). Fully observable PMU configuration which based on theoretical analysis is perfect, but in the actual work, the method seems to be a little waste of resources. Suppose all the nodes in the system as the same, so when we pretend to install on the system dozens to hundreds of PMU, it will appear to give up before a complete SCADA system inevitably, causing series of problems like huge amounts of data. So, a predominantly PMU with SCADA system can be state estimation method of observation system. First of all, in the WAMS system installed - PMU on the system need to stand apart from the different factory, in the system some important hub station installation PMU, other station does not install PMU. It considers that when PMU the configuration meet the following requirements, the method as mentioned above can be confirmed.

Firstly, providing the system key link of voltage and current phasor;

Secondly, getting the dynamic variation which can reflect the system main circuit state trajectory;

Thirdly, obtaining the system backbone network frame information.

## 4. Using the state estimation of equivalent measurement transformation to achieve system after substantial state estimation

Therefore the completely observation station only use a few PMU are obtained, considerable system used in data types are divided into: PMU direct measurement data, through the expansion of the mentioned in the literature [11] provide measurement, and the article mentioned above through the SCADA class PMU data vector transform. As PMU measured directly to the data precision is higher comparing with the SCADA data, so is necessary to give high weight of PMU data, for the extension of the measurement is obtained by PMU gives higher weights, given by SCADA measurement transformation to get the data of the lowest weight value. It can be used to supplement some PMU insufficient data points.

Analysis of objectivity system transformation and equivalent measurement, according to the type (6), the estimation of the station which were not installed PMU device factory are obtained, these estimates can be used to supplement the observable system PMU values, forming a system.

For treating the data which got by the measurement transformation of the SCADA system, it can be assumed that they are collected at the same time, namely in the RTU data acquisition card by using the same sampling pulse can, assumes node p voltage $U_p$ is PMU quantity measure of value, is directly observed, the node voltage instantaneous value is: $u_p=\sqrt{2}U_p\sin(wt+\varphi)$ , $U_p$ is valid, $w$ as the angular frequency, $\varphi$ for the initial phase angle. Pseudo measurement is through the data directly calculate PMU, the PMU measurement values and calculated value $u_p$ at any time t is known. The

SCADA system, the time coordinates $t_s$ of voltage phasor measurement $U_p^s$ is unknown, but there are about 20 PMU data among each two SCADA data, SCADA can be found value $u_p^{mt_0}$ at a particular time $t_a$ in a cycle , make $\left|u_p^{mt_0} - U_p^s\right| = \min\left|u_p - U_p^s\right|$, we can think of the time coordinate $t_a$ for SCADA data, it can be used to supplement data PMU.

According to the analysis of state estimation algorithm in this paper, the transformation state estimation algorithm which based on equivalent current measurement steps are shown as follows:

a: determining the observed system under PMU configuration points;

b: input the original data;

c: according to the type (6), (7) get class PMU value;

d: got the unbalanced observation of state estimation deviation value $H^T R^{-1}(z - h(x))$;

e: based on the corresponding node type (8) obtained current weight;

f: on the basis of calculating the tide of the whole network distribution and the relevant measure of state estimation;

## 5. Example analysis

IEEE14-node system wiring is shown in Figure.1. According to the method simulation which belongs to IEEE14, the amount of phase voltage and current of the PMU of the standard deviation is 0.006,The standard deviation of the measurement data in SCADA system is 0.02, and the mean error and mean error of measured data is 0.

### 5.1 The influence of different PMU device number to the state estimation

Comparison of the three kinds of state estimation method, method 1 is used in this paper, the PMU configuration number is 5, method 2 is nodes which are equipped with PMU state estimation method, the PMU number is 13, method 3 is the traditional use of state estimation method, the PMU number is 8.

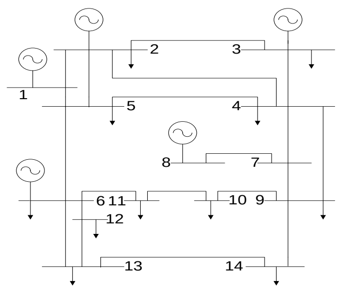


Fig.1 IEEE14-node system

Tab.1 Standard deviations of state estimation under 3 ways

| Busbar number | Method1 Amplitude standard deviation $10^{-3}$ | Method1 Phase angle standard deviation $10^{-3}$ | Method2 Amplitude standard deviation $10^{-3}$ | Method2 Phase angle standard deviation $10^{-3}$ | Method3 Amplitude standard deviation $10^{-3}$ | Method3 Phase angle standard deviation $10^{-3}$ |
|---|---|---|---|---|---|---|
| 1 | 0.381 | 0 | 0.376 | 0 | 0.617 | 0 |
| 2 | 0.353 | 0.297 | 0.347 | 0.289 | 0.583 | 0.562 |
| 3 | 0.442 | 0.395 | 0.433 | 0.378 | 0.596 | 0.548 |
| 4 | 0.371 | 0.355 | 0.350 | 0.346 | 0.488 | 0.474 |
| 5 | 0.362 | 0.291 | 0.348 | 0.287 | 0.504 | 0.566 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 6 | 0.460 | 0.438 | 0.448 | 0.426 | 0.592 | 0.599 |
| 7 | 0.453 | 0.409 | 0.449 | 0.399 | 0.758 | 0.639 |
| 8 | 0.491 | 0.456 | 0.472 | 0.441 | 0.903 | 0.691 |
| 9 | 0.301 | 0.275 | 0.296 | 0.264 | 0.553 | 0.513 |
| 10 | 0.297 | 0.291 | 0.288 | 0.285 | 0.655 | 0.571 |
| 11 | 0.352 | 0.332 | 0.343 | 0.326 | 0.628 | 0.544 |
| 12 | 0.435 | 0.419 | 0.431 | 0.407 | 0.718 | 0.628 |
| 13 | 0.375 | 0.360 | 0.364 | 0.352 | 0.563 | 0.501 |
| 14 | 0.342 | 0.291 | 0.330 | 0.275 | 0.633 | 0.497 |

According to the data in table one, Fig 2 and Fig 3, three amplitude standard deviation curves and Phase Angle standard deviation curves under 3 ways are obtained as follow.

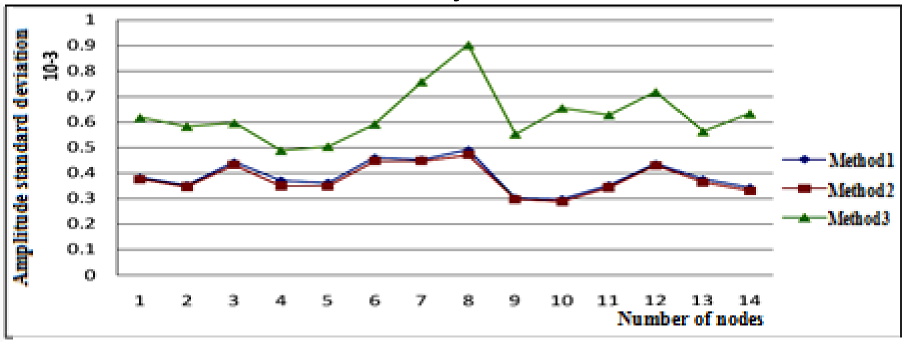


Fig.2 amplitude standard deviation curve under 3 ways

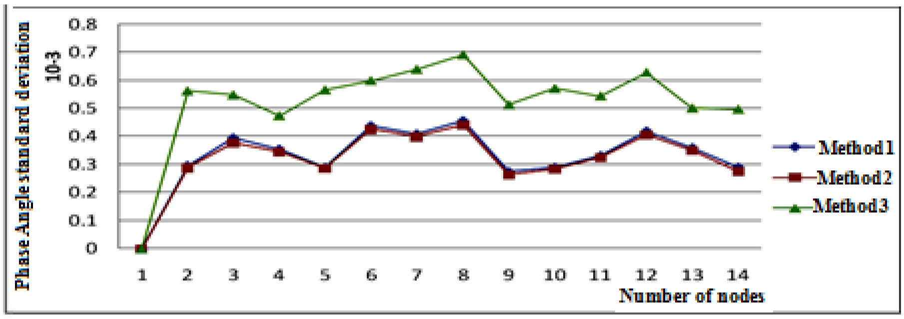


Fig.3 Phase Angle standard deviation curve under 3 ways

It can be seen from Figure 2 and figure 3 that the amplitude standard method can be used in the 2 state estimation and the observation method of the 1 estimate of the difference and phase angle standard deviation is rarely, and far less than the traditional state estimation method of standard deviation of 3.

Table2 Comparison of three different algorithms

| Method | Iterations | State estimated time/s |
|---|---|---|
| 1 | 3 | 0.042 |
| 2 | 2 | 0.038 |
| 3 | 6 | 0.109 |

From table 3, it can be concluded that using the state estimation method in the number of iterations and time have advantages.

### 5.2 The influence of same number PMU device to the state estimation

Method 1 is used in this paper, and method 2 is the traditional state estimation. 3, 5, 8 PMU device are configured in the IEEE14 node in the system, the number of iterations and the state estimation of time.

Table3 3 PMU device under the two different methods of performance comparison

| Method | Iterations | State estimated time/s |
|---|---|---|
| 1 | 7 | 0.126 |
| 2 | 11 | 0.183 |

It can be seen from table 3 that when the number of PMU system is less, more iterations are in the two methods, state estimation needs a long period of time, but the time of the method used in this paper is much less than the traditional method for state estimation.

Table4 5 PMU device under the two different methods of performance comparison

| Method | Iterations | State estimated time/s |
|---|---|---|
| 1 | 3 | 0.042 |
| 2 | 9 | 0.165 |

The Fig.4 indicates that when the number of system configuration of PMU reached to 5, the number of iterative in the method proposed in this paper has been far less than traditional one.

Table5 8 PMU device under the two different methods of performance comparison

| Method | Iterations | State estimated time/s |
|---|---|---|
| 1 | 2 | 0.040 |
| 2 | 6 | 0.109 |

From table 2, table 5 we can see that, when the number of system configuration of PMU reached to 8, comparing with the all PMU device node configuration, the time of state estimation of the method which used in this paper did not existed big difference, and the traditional state estimation method still needs a long time.

Also can know from table 3, table 4 and table 5, along with the gradual increase of the PMU number, the state estimation method to estimate the time system are all nearly to the state of the PMU node device. The method 1 use of the nodal injection power measurement equivalent measurement transformation, virtual PMU data is equivalent to an increase of without the PMU node, which reduces the number of iterations, improving the observability of the global. Compared with the traditional state estimation method of 2, the fewer the iterations are, and the state estimation needs a shorter time. To enhance the practicability of state estimation, at the same time we can see, when the amount of PMU, method 1 of the time to reduce the estimation method more, less time, less the 2 that. Compared to the 2 method, 1 is more suitable for the increasing condition.

## 6. Conclusion

Based on the idea for mainly using PMU data, this paper proposes a PMU system to improve the state estimation method combine with the original SCADA system. This method can reduce the number of configuration PMU, configuration of PMU estimation and state estimation method. When compared with traditional state, it needs less time and iterative state estimation at the same time, with the increase of PMU device, the state estimation of time and number of iterations can be reduced on the basis of the original. In terms of accuracy than the traditional state estimation is much higher than all the configuration of the PMU system, and it can meet the precision requirements of power system, and effectively solve the problem of a large number of configuration due to the massive amounts of data generated by PMU, is a simple and effective estimation method of the state.

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## Reference documentation

[1] Phadke A G. Synchronized phasor measurements in power system. IEEE Computer Applications in Power, 1993, 6(2):10-15.

[2] Phadke A Get al. Synchronized sampling and phasor measurements for relaying and control. IEEE Trans on PD, 1994, 19(1):442-449.

[3] Wilson R E, Sterlina P S. Verification of measured transmission system phase angles. IEEE Trans on PD, 1996, 11(4):1743-1747.

[4] Hauer J F, Validation of phasor calculations in the Macrodyne PMU for California-Oregon transmission project tests of March 1993. IEEE Trans on PD, 1996, 11(3):1224-1231.

[5] People's Republic of China National Development and Reform Commission. Power system time synchronization system - Part 1 Technical Specification [s]. National Development and Reform Commission of People's Republic of China, 2008.

[6] Chen Shi, Xu Yong and so on. Grid real-time dynamic monitoring technology and application [M]. Beijing China Water&Power Press.2010.

[7] Phadke A G, Thorp J S, Karimi K J. State estimation with phsor measurements[J]. IEEE Trans on Power Systems, 1986, 1(1):233-241.

[8] Naduvathuparambil B, Valenti M C, Feliachi A. Communication delays in wide area measurement systems [C]. Proceedings of the 34thSoutheastern Symposium on SystemTheory, Huntsville, 2002:118-122.

[9] Zhao Hong-ga , Xue Yu-sheng , Wang De-xing , state estimation model with PMU current phasor measurements, Automation of Electric Power Systems,2004,28(17):37-40.

[10] LU Zhi-gang,ZHANG Zong-wei,Network Observability Analysis Based on Linear Dependence between Measurement Function Vectors, Power System Technology2007, 31（17）:51-55.

[11] Peng Jiangnan, Sun Yuanzhang,Wang Haifeng, an optimal PMU placement algorithm for full network observability, Automation of Electric Power Systems, 2003, 7（4）10-16.

[12] Wang Shao, Jiang Zhuo-han. Power system state estimation based on singular value decomposition and equivalent current measurement transformation[J]. Power System Protection and Control. 201240（12）, 111-114.

[13] CHEN Fang, HAN Xue-shan, LI Hua-dong. Decomposition and coordination state estimation based on PMU[J]. Power System Protection and Control. 2009,37(1),44-48.

[14] ZHAO Liang,QIAN Yu-chun,GU Quan,CHEN Gen-jun.State estimation of dynamic process based on equivalent model[J],Power System Protection and Control ,2010.38(11).10-14.

[15] GUO Hua.ZHANG BoMing.WU WenChuan.Contain zero injection constraint in the cartesian coordinates of power system state estimation modified Newton method[J]. Proceedings of the CSEE,2012, 32(19):96~100.