Available online at www.sciencedirect.com

ScienceDirect

IFAC-PapersOnLine 49-27 (2016) 461–466

Development of a State Estimation Methodology to Improve the Quality of Control of the Boundary Areas of the Neighboring Smart Transmission Grids

Kolosok, I.* Korkina, E.*

*Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS), Russia (Tel: +7395-2500-646 ext. 236; e-mail: kolosok@isem.irk.ru).

Abstract: The reliable failure-free operation of electric power systems requires valid initial data. Technical failures or impact of cyber-attacks can cause partial loss or corruption of these data. If this happens at the boundary of the neighboring electric power systems, owing to their mutually supportive collaboration it will be possible to verify the information in one electric power system using the measurements from a boundary area of a neighboring power system.

Keywords: State Estimation, boundary conditions, monitoring, cyber-attack, PMU, WAMS.

1. INTRODUCTION

An international integration of the electric power systems provides certain advantages in the field of operation security and energy exchange by ensuring mutual backup of collaborating power systems in case of emergency. Since the power systems differ in their technical characteristics, the technical and economic efficiency of their collaboration depend on the technologies applied by them. Such an interaction is more productive when equipment and software are compatible in accordance with the international standards and requires carefully selected methods for monitoring of large-scale power systems and their control. There is some experience in solving the problems of monitoring the Russian electric power system together with the electric power systems of neighboring countries (The main technical requirements).

High levels of reliability and efficiency of energy system operation can be provided only by applying smart technologies. In 2012 Russia developed a concept of intelligent power systems (Berdnikov et al) that places an emphasis on the importance of the development of technologies for monitoring Smart Grid and diagnosing the networks; new principles of information interaction of energy facilities that imply digitalization, of the data exchange on the basis of MEC protocols and provision of their cyber security. New capabilities of monitoring the load flow parameters and their control are afforded by the wide-area measurement system (WAMS). Observability of the calculated schemes of the energy facilities increases with a rise in the number of installed PMUs in WAMS. The application area of PMU measurements in electric power systems is rather wide: from visualization of the conditions directly on the basis of PMU measurements to the adaptive control of electric power systems in transient conditions (Chusovitin et al).

This study is supported by the grant of Russian Leading Scientific School #6941.2016.8.

As was noted in (Hager et al), monitoring and control of large-scale interacting systems requires advanced state estimation (SE) which provides more accurate data about the electric power system (EPS) which initiates the state estimation procedure and about its neighboring power systems, which is a guarantee of correct control actions in case of failures and emergencies in large-scale systems. The ICOEUR project in 2009-2012 considered the distributed SE algorithms that were developed at the Energy Systems Institute on the basis of a new generation of measurements, and tested them on the measurements of the Baltic ring scheme. The obtained results confirmed the correctness of the approaches to the technology of monitoring in current conditions.

More stringent requirements are imposed on the quality of measurements applied to the state estimation of boundary areas since the distortion of state variables in these areas can lead to errors in control with severe technological and economic consequences. At the same time WAMS, which is based on the sophisticated computer and communication equipment, itself is an object of cyber-attacks that lead to falsification, loss, delay and desynchronization of PMU measurements and other negative effects which in the end results in the deterioration of SE results. The presence of PMU measurements in the boundary areas of neighboring power systems gives an opportunity to use them to verify their measurements and additionally verify the "neighboring" measurements.

To solve such a problem, this research suggests the method of test equations (TE) which was developed to detect bad data in the SCADA measurements (Gamm et al), and then adapted to test PMU measurements and analyze cyber security of SCADA and WAMS (Kolosok et al, 2014a, b).

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2016.10.776

2. DEVELOPMENT OF TEST EQUATION METHOD: FROM SCADA TO WAMS

The Test Equation Method. All calculations in the state estimation problem are based on the state vector $x = \{\delta, U\}$, which includes voltage magnitudes U and phase angles δ at all nodes of the power system network except for the phase of a reference node. Such a state vector uniquely determines all the measured variables y

$$y = H(x), \tag{1}$$

Along with the traditional approaches (Handschin et al), (Montically, etc.) there is the test equation (TE) method developed at ESI SB RAS (Gamm et al). Test equations (TE) are steady-state equations which contain only measured state variables y

$$w_{TE}(y) = 0. \tag{2}$$

One of the possible methods to obtain TEs is the exclusion of state vector components x from (1):

$$y - H(x) = 0. \tag{3}$$

To this end equations (3), nonlinear in general, get linearized and then all measurements are divided into basic[1] y_b and redundant[2] y_r, which makes it possible to determine $x = f(y_b)$ and by substituting them to equations (1) for y_r, obtain the test equation. The state estimation by the method of test equations consists in the minimization of the criterion

$$J(y) = (\bar{y} - \hat{y})^T R_y^{-1} (\bar{y} - \hat{y}) \tag{4}$$

under the equality constraints represented by a system of TEs (2). (R_y is a covariance matrix of measurement errors). To solve the system of equations we make up the Lagrange function (where λ – vector of uncertain Lagrange multipliers)

$$L = J(y) + \lambda\, w_{TE}(y), \tag{5}$$

whose minimization gives the expression for the determination of the estimates of measured variables:

$$\hat{y}^{(i+1)} = \hat{y}^{(i)} - R\left(\frac{\partial w_{TE}}{\partial y}\right)^T \left[\left(\frac{\partial w_{TE}}{\partial y}\right) R_y \left(\frac{\partial w_{TE}}{\partial y}\right)^T\right]^{-1} w_{TE}(\hat{y}^{(i)}) \tag{6}$$

where i - number of iteration. The SE algorithms based on TE are less laborious than the algorithms of the traditional state estimation and very fast because the TE system order is, as a rule, essentially lower than the order of the initial system of steady-state equations (1) which is used to obtain test equations.

The algorithms of linear state estimation by the method of test equations, using the PMU data. Both in the electric power system of Russia and in the electric power systems of neighboring countries PMUs are installed at EPS facilities that are the most "crucial" in terms of control. For the areas completely observed on the basis of PMU measurements the linear state estimation can be made which provides fast and accurate solution.

For node i, at which PMU is installed, we can obtain the measurements of magnitudes and phases of voltages U_i, δ_i, and currents I_{ij}, ψ_{ij} as well as $U_{i(j)}, \delta_{i(j)}$, that are calculated through the measurements of the physical PMU installed at the adjacent node j. According to the terms established in (Nuqui) the measurements U and δ calculated in such a way are called "calculated" PMU. The accuracy of measurements of the "calculated" PMU practically equals the accuracy of measurements of the physical PMU (Kolosok et al, 2009).

The SE problem using PMU measurements when solved in rectangular coordinates becomes linear: state vector of the system is $x = \{\dot{U}_i\}$, where $\dot{U}_i = U_{i_a} + jU_{i_r}$ complex numbers of nodal voltages. Vector of measurements is represented by complex vector $\bar{y} = \{\dot{U}_i, \dot{I}_{ij}, \dot{I}_i\}$, where $\dot{I}_i = I_{i_a} + jI_{i_r}$ and $\dot{I}_{ij} = I_{ij\,a} + jI_{ij\,r}$ are complex numbers of electrical current measurements in lines and at nodes.

By virtue of linear character of relationships between current and voltage the Jacobi matrix H is a constant matrix with the elements equal to conductances and susceptances of branches. To exclude state vector components we apply the procedure of triangulation of matrices H to (3) by the Crout method, adapted by authors (Gamm et al), (Kolosok et al, 2014b) to the factorization of rectangular matrices. This factorization allows us to calculate matrix of coefficients of the system of test equations D and write the system of test equations relating the redundant measurements and basic ones in the following form:

$$y_r - D\, y_b = 0. \tag{7}$$

The obtained test equations are linear. The test equations are used to make a priori verification of measurements in order to detect and suppress bad data. The substitution of the obtained measurements into these test equations results in discrepancies due to measurement errors. Comparing the value of TE discrepancies with some threshold d, i.e. checking the condition

$$|w_k| < d, \tag{8}$$

we can judge whether or not the measurements entering this test equation contain bad data. Now it is well known that the measurements of PMU may have bad data that considerably distort the state estimation results, therefore when using the PMU measurements to solve the problems of control it is necessary to verify them (Kolosok et al, 2014b).

The results of verification are responsible for the formation of vector of measurements for the state estimation of a local area (Glazunova et al) observed on the basis of PMU

---

[1] The basic measurements are a minimum set of measurements that provide observability of electric power system.

[2] The redundant measurements are the measurements which remain in a set of measurements after the basic measurements have been excluded.