Real-Time Identification and Estimation of Transformer Tap Ratios Containing Errors

Hongrae Kim and Hyung-Seok Kwon

Abstract - This paper addresses the issue of parameter error identification and estimation in electric power systems. Parameter error identification and estimation is carried out as a part of the state estimation. A two stage estimation procedure is used to detect and identify parameter errors. Suspected parameters are identified by the WLAV state estimator in the first stage. A new WLAV state estimator adding suspected system parameters in the state vector is used to estimate the exact values of parameters. Supporting examples are given by using the IEEE 14 bus system.

Keywords - power system state estimation, parameter errors, linear programming, weighted least absolute value

1. Introduction

Since Fred Schweppe first introduced the basic theory of Power System State Estimation[1], various methods for state estimation such as the weighted least squares(WLS) method, the weighted least absolute value(WLAV) method, the least median squares(LMS) method, etc, have been introduced. Nowadays, power system state estimation is an intrinsic part of almost every Energy Management System for the secure operation of power systems[2, 3].

A power system state estimation program processes a set of raw measurement data, including bus voltage magnitudes, real and reactive power injections at the buses, real and reactive line power flows, etc, collected by the SCADA system and provides a real-time load flow solution providing a database for subsequent network analysis functions.

Power system state estimators use two kinds of data: on-line analog measurement data and system parameter data such as line impedances, tap ratios of transformers, etc. Parameter errors occurring in power systems may affect the result of the state estimation and lead to wrong solutions even worse than including bad measurements in the data set. The performance of state estimation, therefore, depends on the accuracy of the measured data as well as the parameters of the system model. Bad data processing is now a standard sub-function in most state estimation packages[4-7]. However, the work on handling parameter errors is not filed completely yet.

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Early studies on processing parameter errors are introduced by Merrill and Schweppe[8]. Their method must have enough redundancy of the measurement data related to the parameters to be estimated. Debs introduces the method where a system parameter is estimated by a recursive algorithm using a Kalman filter[9].

In this paper, the estimation of the tap ratios of transformers is discussed as an example of the parameter error estimation. In section II, a brief review of the WLAV state estimation is presented. In section III, a system model for parameter error estimation is described. Measurement functions for bus power injections and line power flows are derived in section IV. Case studies carried out on the IEEE 14-bus test system are presented in section V. Finally, some conclusions on the results of this paper are made in section VI.

2. WLAV State Estimation

Since the weighted least absolute value state estimator was introduced by Irving, Owen, and Sterling [10], several studies have been presented on this method. The greatest advantage of the WLAV state estimator is its robustness against gross errors including multiple interacting bad data except for those associated with leverage points. The leverage points are caused by the large imbalances in the weights of the measurement data, short and long transmission lines terminated at the same bus, etc. There have been studies to improve the robustness of the WLAV estimator[11, 12].

The mathematical model of state estimation is based on the relationship between the measurement data and the state vector that is given by

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

where,

z : the measurement vector of dimension (m×1),
x : the state vector of dimension (n×1),
$h(x)$: the nonlinear measurement,
e : the measurement noise vector of (m×1),
m : the number of measurements,
n : the number of state variables.

The WLAV state estimates can be obtained by minimizing the following objective function:

$$J(x) = \sum_{i=1}^{m} \omega_i | z_i - h_i(x) | \tag{2}$$

The objective function of Eq.(2) can be minimized by calculating a linear programming problem of Eq.(3) and Eq.(4) iteratively[13, 14].

$$J(x) = \sum_{i=1}^{m} \omega_i \cdot (u_i + v_i) \tag{3}$$

$$\Delta z^k = H(x^k) \cdot \Delta x^k + u - v \tag{4}$$

where,
Δz^k: $z - h(x^k)$
$H(x^k)$: $\partial h / \partial x$ at $x = x^k$,
w_i : weight assigned to the measurement i,
u, v : nonnegative slack variables,
$(u - v)$: the measurement residuals.

3. System Modelling

In order to detect the parameter errors and estimate the accurate values of the parameter errors, a two step procedure is proposed. The first step of estimation uses a bus level network model as in conventional WLAV estimators. Results of step 1 are used to draw a set of suspect transformers whose tap ratios may be erroneous. In the second step, the identified transformers are modeled in detail using the tap changing transformer models while keeping the bus level network models for the rest of the system.

A model for tap changing transformers is shown in Fig. 1. y_{km} is the admittance between bus k and m, and t is the tap ratio. The bus admittance matrix for the system in Fig. 1 can be written as:

$$Y_{bus} = \begin{bmatrix} \frac{y_{km}}{t} + \frac{1}{t} \cdot (\frac{1}{t} - 1) y_{km} & -\frac{y_{km}}{t} \\ -\frac{y_{km}}{t} & \frac{y_{km}}{t} + (1 - \frac{1}{t}) y_{km} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{y_{km}}{t^2} & -\frac{y_{km}}{t} \\ -\frac{y_{km}}{t} & y_{km} \end{bmatrix}$$

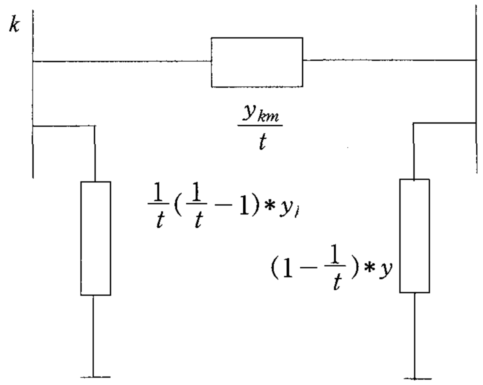

Fig. 1 Model of Tap Changing Transformer

4. Measurement Functions

4.1 Bus Power Injections

When a tap changing transformer is connected between bus i and bus j, the expressions for real and reactive power injections are written as:

$$P_i = P_{i1} + P_{i2} \tag{5}$$

$$Q_i = Q_{i1} + Q_{i2} \tag{6}$$

where,

$$P_{i1} = \sum_{m=1}^{n} V_i V_m (G_{im} \cos \theta_{im} + B_{im} \sin \theta_{im}),$$

$$P_{i2} = V_i V_m (G_{im} \cos \theta_{im} + \frac{1}{x_{ij}} \cdot \frac{1}{t_{ij}} \sin \theta_{im}),$$

$$Q_{i1} = \sum_{m=1}^{n} V_i V_m (G_{im} \sin \theta_{im} - B_{im} \cos \theta_{im}),$$

$$Q_{i2} = V_i V_m (G_{im} \sin \theta_{im} - \frac{1}{x_{ij}} \cdot \frac{1}{t_{ij}} \cos \theta_{im}),$$

V_i : voltage magnitude at bus i,
V_m : voltage magnitude at bus m,
θ_{im} : voltage angle difference, $\theta_i - \theta_m$,
G_{im} : real part of the (i,m)th element of the bus admittance matrix,
B_{im} : reactive part of the (i,m)th element of the bus admittance matrix,
x_{ij} : the reactance between bus i and bus j,
t_{ij} : the tap ratios between bus i and bus j.

4.2 Line Power Flows

Since the line charging admittances of bus k and bus m are not equal, measurement functions for line power flows from bus k to bus m and bus m to bus k are different and should be derived separately.

The measurement functions of real and reactive power flows from bus k to bus m are written as:

$$P_{km} = V_k V_m(G_{km}\cos\theta_{km} + \frac{1}{x_{km}}\cdot\frac{1}{t_{km}}\sin\theta_{km}) - V_k^2(G_{km} - G'_{km}) \quad (7)$$

$$Q_{km} = V_k V_m(G_{km}\sin\theta_{km} - \frac{1}{x_{km}}\cdot\frac{1}{t_{km}}\cos\theta_{km}) + V_k^2\cdot\left[\frac{1}{x_{km}}\times\frac{1}{t_{km}} + \frac{1}{x_{km}}\times(\frac{1}{t_{km}^2} - \frac{1}{t_{km}})\right] \quad (8)$$

The measurement functions of line power flows from bus m to bus k are written as:

$$P_{km} = V_k V_m(G_{km}\cos\theta_{km} + \frac{1}{x_{km}}\cdot\frac{1}{t_{km}}\sin\theta_{km}) - V_m^2(G_{km} - G'_{km}) \quad (9)$$

$$Q_{km} = V_k V_m(G_{km}\sin\theta_{km} - \frac{1}{x_{km}}\cdot\frac{1}{t_{km}}\cos\theta_{km}) + V_m^2\cdot\left[\frac{1}{x_{km}}\times\frac{1}{t_{km}} + \frac{1}{x_{km}}\times(1 - \frac{1}{t_{km}})\right] \quad (10)$$

where,

G'_{km} , B'_{km} : a half of the line charging admittance.

4.3 Jacobian Matrix

The elements of the Jacobian matrix are derived by taking the partial derivatives of the measurement functions with respect to the voltage magnitudes, phase angles, and the transformer tap ratios.

$$H(x) = \begin{bmatrix} 0 & \partial V_k/\partial V & \partial V_k/\partial t \\ \partial P_k/\partial\theta & \partial P_k/\partial V & \partial P_k/\partial t \\ \partial Q_k/\partial\theta & \partial Q_k/\partial V & \partial Q_k/\partial t \\ \partial P_{km}/\partial\theta & \partial P_{km}/\partial V & \partial P_{km}/\partial t \\ \partial Q_{km}/\partial\theta & \partial Q_{km}/\partial V & \partial Q_{km}/\partial t \end{bmatrix} \quad (11)$$

$$\partial P_i/\partial\theta_j = V_i V_j(G_{ij}\sin\theta_{ij} - \frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ij}),\ i\neq j$$

$$\partial Q_i/\partial\theta_j = -V_i V_j(G_{ij}\cos\theta_{ij} + \frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\sin\theta_{ij}),\ i\neq j$$

$$\partial P_i/\partial\theta_i = -\left[Q_i + V_i^2\cdot\left\{\frac{1}{t_{ij}^2}\cdot(-\frac{1}{x_{ij}}) + TEMP\right\}\right],$$

$$\partial Q_i/\partial\theta_i = P_i - V_i^2\cdot G_{ii}$$

$$\partial P_i/\partial V_j = V_i(G_{ij}\cos\theta_{ij} + \frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\sin\theta_{ij}),\quad i\neq j$$

$$\partial Q_i/\partial V_j = V_i(G_{ij}\sin\theta_{ij} - \frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ij}),\quad i\neq j$$

$$\partial P_i/\partial V_i = (P_i + V_i^2 G_{ii})/ V_i$$

$$\partial Q_i/\partial V_i = \left[Q_i - V_i^2\cdot\left\{\frac{1}{t_{ij}^2}\cdot(-\frac{1}{x_{ij}}) + TEMP\right\}\right]/ V_i,$$

$$TEMP = \sum_{m=1}^{n} B_{im} \quad (j\neq m)$$

$$\partial P_{ij}/\partial\theta_i = V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ij})$$

$$\partial P_{ij}/\partial\theta_j = -\partial P_{ij}/\partial\theta_i = -V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ij})$$

$$\partial Q_{ij}/\partial\theta_i = V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\sin\theta_{ij})$$

$$\partial Q_{ij}/\partial\theta_j = -\partial Q_{ij}/\partial\theta_i = -V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\sin\theta_{ij})$$

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$$\partial P_{ij}/\partial V_i = V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\sin\theta_{ij})$$

$$\partial Q_{ij}/\partial V_j = -V_i(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ij})$$

$$\partial Q_{ij}/\partial V_i = 2 V_i\cdot(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}) - V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ij})$$

$$\partial Q_{ji}/\partial V_j = 2\cdot V_j\cdot\frac{1}{x_{ij}} - V_i(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}}\cos\theta_{ji})$$

$$\partial P_i/\partial t = -V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}\sin\theta_{ij})$$

$$\partial Q_i/\partial t = -2V_i^2(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^3}) + V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}\cos\theta_{ij})$$

$$\partial Q_j/\partial t = V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}\cos\theta_{ij})$$

$$\partial P_{ij}/\partial t = -V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}\sin\theta_{ij})$$

$$\partial Q_{ij}/\partial t = V_i V_j(\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}\cos\theta_{ij}) - 2\cdot V_i\cdot\frac{1}{t_{ij}}$$

$$\partial Q_{ji}/\partial t = V_i V_j\cdot\frac{1}{x_{ij}}\cdot\frac{1}{t_{ij}^2}\cos\theta_{ji}$$

5. Simulations and Results

The transformer tap ratio estimation program is developed, and supporting examples are given by using the IEEE 14 bus system as shown in Fig. 2.

The accurate tap ratios of the transformers connected between bus 4 and bus 7 and between bus 4 and bus 9 are 0.978 and 0.969, respectively. It is assumed that the tap ratios of the transformers have 5% and 10% errors. In the first stage, the program finds measurement data which have the normalized residuals larger than 3.0, and then identifies the transformer to which the suspect measurements are incident the most number of times.

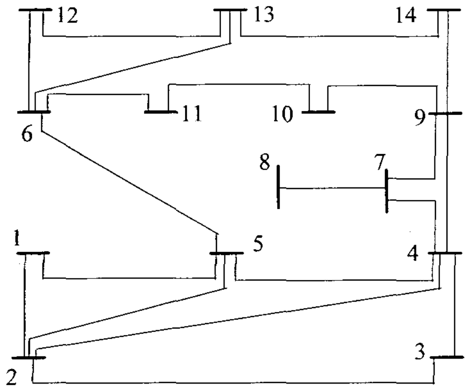

Fig. 2 IEEE 14-bus Test System

In the second stage, the tap ratio of the suspected transformer is set as a new state variable and added to the state vector. The state Estimation process is repeated for the estimation of the exact tap value. The results are summarized in Table 1 and Table 2.

Table 1 Estimation Procedure of the Tap Ratio of the Transformer between Bus 4 and 7

	Tap Ratio in Error	
	0.9291(5% Error)	0.8801(10% Error)
r_N >3.0	10.319(Qflow 7-4) -9.462(Qflow 4-7) 8.770(Qinj 7) -3.914(Qinj 4)	25.676(Qflow 7-4) -21.996(Qflow 4-7) 19.718(Qinj 7) -6.731(Qinj 4)
Estimated Tap Ratio	0.97803	0.97803
Max. r_N	-2.193(Qflow 11-6)	

Table 2 Estimation Procedure of the Tap Ratio of the Transformer between Bus 4 and 9

	Tap Ratio in Error	
	0.92(5% Error)	0.87(10% Error)
r_N >3.0	3.0278(Qflow 9-4)	9.462(Qflow 9-4) 8.056(Qinj 9) -7.887(Qflow 4-9)
Estimated Tap Ratio	0.96899	0.96899
Max. r_N	-1.789(Qflow 14-13)	

6. Conclusions

This paper investigates the identification and estimation problem of transformer tap ratio errors. The problem is proposed to be solved by a modified two stage WLAV state estimator. Since WLAV estimators converge in the presence of parameter errors (transformer tap ratio errors), normalized measurement residuals at the first stage carry information about the location of the possible errors. This information is used to localize the transformer to be estimated in the second stage. Simulations with the IEEE 14-bus system verify the propriety of the proposal algorithm.

The new modeling needs to be associated with the introduction of new control devices and the changes induced by emerging energy markets are making state estimation and its related functions more important than ever.

Acknowledgments

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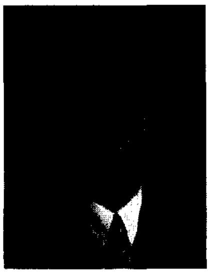

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