TELKOMNIKA, Vol.11, No.3, March 2013, pp. 1714~1720
ISSN: 2302-4046

Study on Practical Issues for the State Estimation of the Automatic Voltage Control System

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Abstract

The state estimation is an important part of the automatic voltage control (AVC) system, and it is the basis of the advanced software application for the electric power systems (EPSs). This paper presents the status quo of the current state estimation mathematical model and the actual grid state estimation applications. The actual AVC system network modeling and model validation, pre-processing and other related issues are discussed, and the methods for detection and identification of bad data are presented. Besides, the debugging method of state estimation for enhancing practical pass-rate is proposed. Finally, the state estimation of the actual system is validated, and the results show that the state pass-rate is more than 99%, which has important significance for the AVC control practitioners and power flow dispatchers.

Keywords: *State estimation, automatic voltage control, adjusting method, model validation*

1. Introduction

The state estimation is an important part of the automatic voltage control (AVC) system, which utilizes the redundancy of the real-time measurement data to improve data filtering, and automatically excludes the random interference and noise caused by the error message, hence estimates or forecasts the operation status of the system [1-5].

Since the error of grid telemetry is inevitable for the practical system, and the telemetry coverage and available rate of the telemetry signals may be less than 100%, the state estimation is based on the redundant telemetry signals, and the inherent constraints of the electric power system (EPS) and the statistical probability principles to exclude telemetry error of the signals, and reduce errors, thus achieves a relatively accurate and complete operation state [6, 7]. Moreover, the SCADA system of the remote signaling telemetry re-checks the accuracy of the states, and the abnormal telemetry points are uncovered. Hence, the outcome of the state estimation shows significance for the AVC controller designers and the power flow dispatchers [8].

Firstly, the mathematical model of the existing state estimation schemes are reviewed, and it is combined with the actual state estimation of the grid. The actual network model of the AVC system and model validation is summarized, followed by the pre-processing and the related bad data detection and identification methods are presented. The effective debugging method to increase the pass rate is proposed. Finally, by the debugging method is validated by the state estimation of the actual electrical power system (EPS).

2. The Mathematical Model of State Estimation

The measurement equation of the electric power system (EPS) can be expressed as:

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

where z denotes the vector of the measurement data, $h(x)$ denotes the vector of the calculated data, v denotes the detection error. Assuming the measurement is performed m times, hence

Received June 17, 2012; Revised September 10, 2012; Accepted October 19, 2012

the vector in equation (1) is m-dimensional, and *x* denotes the state variable, *n* denotes the number of nodes, hence *x* is (2*n*-1)-dimensional. When the measurement vector *z* is given, the estimation vector $\hat{x}$ satisfies the following objective function:

$$J(x) = [z - h(x)]^T R^{-1}[z - h(x)] = \sum_{i=1}^{n}(r_i/\sigma_i)^2 \rightarrow \min \quad (2)$$

where R^{-1} denotes the weighting matrix, the diagonal elements σ_i^2 form the *m*×*n* diagonal matrix。In order to estimate $\hat{x}$, the following iteration algorithm is applied:

$$\Delta x^{(l)} = [H^T(x^{(l)})R^{-1}H(x^{(l)})]^{-1}H^T(x^{(l)})R^{-1}[z - h(x)] \quad (3)$$

$$x^{(l+1)} = x^{(l)} + \Delta x^{(l)} \quad (4)$$

where $H(x) = \partial h(x)/\partial x$ denotes the Jacobian matrix of the algorithm, *l* denotes the iteration times.

3. The Debugging Method for the State Estimation Algorithm

3.1. Network Modeling and Model Validation

Prior to the state estimation process, the network modeling is required to set up the electrical connection with the grid, the input parameters are kept consistent with the actual parameters of the device as much as possible, and appropriate equivalents are allowed. At the same time, the external network is represented by its equivalent network, and the principle of external line equivalents is that, the regional subsystem which provides active power is represented by the generator, and the network which absorbs active power is represented by the load. Under normal circumstances, the boundary line of the 220kV network is represented as a generator, the equivalents of 110kV network and below the boundary line is represented as a load. For some of the low voltage line (such as the 10kV line), if no modeling process is taken for the boundary substations, these lines are represented as loads.

After the network modeling is completed, it is necessary to validate the model. The network modeling and model validation flow chart is shown in Figure 1, the state estimation can be achieved only after the model validation is completed. When there is a serious error, the network model cannot be used for the state estimation directly, and a common type of error and error correction method is shown in Table 1.

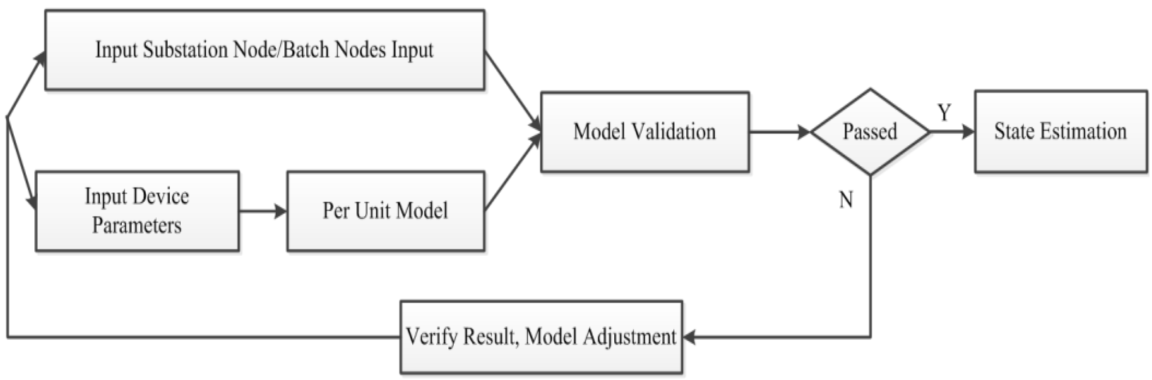

Figure 1 The flowchart of network modeling and model validation

3.2. Preprocessing

Before the main program is executed, the preprocessing is performed for the measurement data obtained from the SCADA system, and the accuracy of the measurement is investigated by using the related information.

Table 1 The typical errors and error correction method

Typical Errors	Error correction method
Lack of parameters or parameter error	Lack of network model parameters
Node number error	Nodes Re-storage for the plant station
Parameter deviation	Device parameters re-investigation
Without Node number	Node re-storage for the related plant station; Deleted the graphic device in the library.
Node Hanging	Don't bother the empty hanging for the secondary and terminal equipment.

As far as the treatment of the telemetry pre-processing, the main concerns are the violation of the telemetry-limit and the telemetry imbalance. The violation of the telemetry-limit focuses on the SCADA remote measurement equipment itself for violation limits investigations. As for the telemetry imbalance, the line and transformer active and reactive powers, the bus injected active and the reactive powers are tested using the data obtained from SCADA measurements

For remote communication pre-processing, if the suspicious switch knife is found, the investigation is needed to check whether there is error in the signals, and the existence of electromagnetic loop network should be investigated.

3.3. The detection and identification of bad data

Generally, the defective data is the error that is greater than a certain standard (3 to 10 times of the standard deviation) of the measurement data. Prior to the state estimation, one must first determine whether there is defective data from the SCADA data. Measurement error data is divided into two categories: Firstly, in case of the stabile wrong number (caused by equipment problems or communication failure), the step-by-step process is used to eliminate erroneous data from telemetry, remote signaling and remote adjustment data. Secondly, the random sampling error generated by the measurement and transmission system or outside interference. One should increase the redundancy of the measurement system, and ensure the observability of the data after the bad data are eliminated.

Usually, the bad data detection methods include the following four categories:

(1) Rough detection method. Verify whether the measurement data exceed the prescribed limit or the change of speed, the error is directly eliminated in SCADA data

(2) Residual detection method. The residual detection methods include the weighted residuals detection and standardized residuals detection. In general case of measurement redundancy for the single bad data detection, the standardized residuals detection performance is superior to the weighted residuals detection method. The residual detection threshold requires manual adjustments in the operation, the initial threshold set high so as not to produce too much suspicious data thereby lose identifiability. It can be set to a lower threshold so as not to miss the bad data in late maintenance when measurement system is in good condition.

(3) Measurement mutation detection. This method is realized by checking the last two times whether the amount of measurement sampling variation is greater than the threshold of detection methods.

(4) Residuals and mutation combined detection method. The total amount of measured data is divided into the suspicious data and the reliable data, and the suspected bad data are identified to ensure the accuracy of the state estimation results. Residual detection is simple and intuitive, but has the drawbacks of the residual submerged and the residual pollution. Mutation detection in the last estimation results are correct, the network structure remains unchanged and load changes can guarantee detection accuracy. Hence the hybrid detection method can be complementary.

Bad data identification methods are as follows:

(1) Residuals search identification method: Requires repeatedly state estimation calculation, and takes a long time, not suitable for large-scale power systems;

(2) Secondary criteria for identification: The suspicious measurements are not excluded directly, but modify its weight in accordance with the residual size during iterations, and the residual reduction of its weight resulting in further iterations to weaken its influence to get more accurate status estimates. This method is effective for strong measurement system with a large

amount of iterative calculations, and identification of weak measurement system often leads to divergence problem.

(3) Zero residual identification method: This method does not change the weight, and the suspicious residuals are directly set to zero to achieve the same purpose.

(4) Successive estimation identification method: This method takes the residuals after successive linear correction between exploratory logic and the estimated residual state, and a successive identification of bad data identification method is set up. But the overall iteration is avoided, thus only a small number of related elements are used for matrix manipulation and calculation to reduce the computational burden.

3.4. The debugging method to improve the pass-rate of state estimation

Based on the problems encountered in the system state estimation, the following section summarizes on how to improve the pass-rate of state estimation method.

In order to increase the estimation accuracy of the active power, several aspects need to be taken into consideration:

(1) Coarse detection: check the main transformer on each side, check the value and sign of the lines active, reactive powers, check the anti-shielding; checks whether there is an imbalance between the bus injection and outflow;

(2) Check whether there are death data and obvious error in the telemetry, since the state estimation of active and reactive powers is paired, if one measurement data is filtered out, its counterpart measurement data will be automatically filtered out;

(3) Check the telemetry of dead-island, and check remote status and check whether there is non-zero value in telemetry when disconnect tele-signaling;

(4) Check the load calculation of the low-voltage side, the state estimation is performed by combining the entire load into one injection value, the obtained the total bus injection load is then allocated to each of the actual physical load.

(5) The presence of a large number of line or transformer with unreasonable active power, check transformer topology whether the positions of the high, medium and low voltage are reversed.

(6) In addition to the above measurement error, the local electrical parameters are also needed to be checked, as well as the external equivalent circuit of active and reactive powers.

4. The Results of State Estimation Algorithm

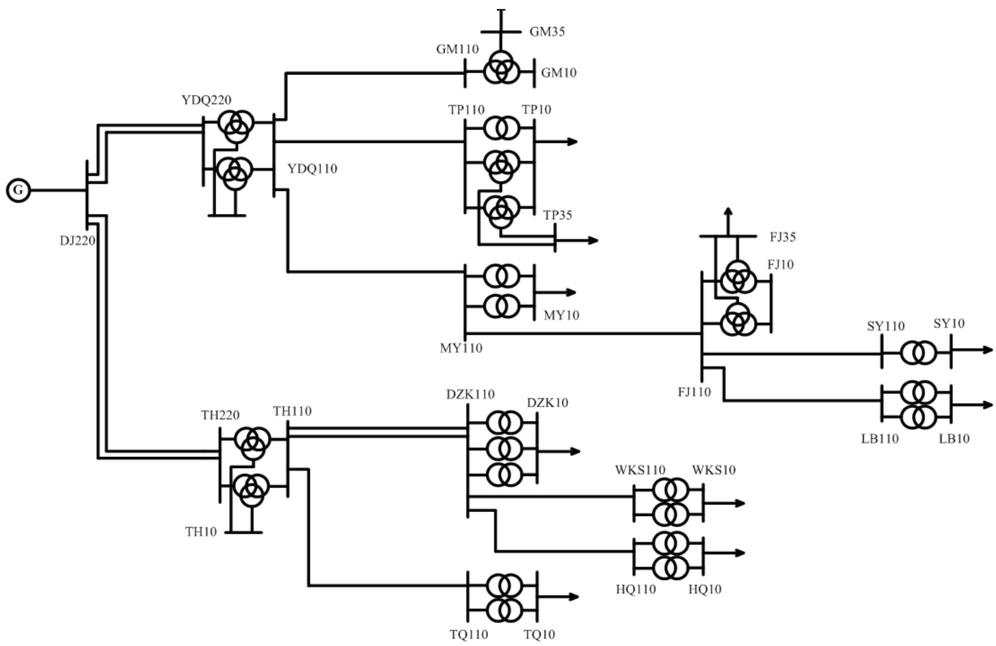

Figure 2 The circuit diagram of the target electric power system

Figure 2 shows the topology of the target research system. Firstly, the node storage is realized in accordance with the flowchart of Figure 1, and the related parameter are used as input, followed by the model validation, the bus voltage, line power, transformer power, the capacitor switch state, the SCADA data are checked consecutively. Based on the above-mentioned state estimation method, the various parameters of the entire system are calculated. Tables 2-5 show the obtained bus voltages, AC line segment active/reactive powers, the load active/reactive powers, transformers the active/reactive powers. The state estimation results obtained from the actual power system show that the systematic state estimation debugging method is reasonable and effective, which provides a technical basis and practical method for the commissioning and maintenance of system estimation for the AVC system.

Table 2 Comparison of data before and after the bus voltage estimation

Substation	Bus	Measurement (kV)	Calculation (kV)
DJ	DJ220	231.26	230.79
DZK	DZK110	114.5	115.32
	DZK10	10.65	10.53
FJ	FJ110	109.78	109.98
	FJ35	34.5	34.5
	FJ10	10.45	10.45
GM	GM110	118.41	118.16
	GM35	36.03	35.99
	GM10	11.02	10.99
HQ	HQ110	113.62	114.5
	HQ10	10.61	10.44
LB	LB110	109.53	109.66
	LB10	10.45	10.58
MY	MY110	113.93	113.71
	MY10	10.89	10.86
SY	SY110	108.99	109.19
	SY10	10.06	10.06
TH	TH220	228.93	228.82
	TH10-I	10.12	10.19
	TH110	116.4	116.86
	TH10-II	10.13	10.19
TP	TP110	112.35	112.67
	TP35	34.14	34.16
	TP10-I	10.39	10.35
	TP10-II	10.68	10.62
TQ	TQ110	114.69	115.16
	TQ10	10.43	10.48
WKS	WKS110	114.42	115.22
	WKS10	10.84	10.67
YDQ	YDQ220	229.58	229.18
	YDQ10	10.18	10.19
	YDQ110	117.55	117.49

Table 3 Comparison of data before and after the exchange of AC-line segments active/reactive state estimation

Substation ID	AC Network	Active Power (MW)	Active power before calculation(MW)	Reactive power(MVar)	Reactive power before calculation(MVar)
DZK	WKS-DZK	10.37	10.61	3.63	6.29
	HQ-DZK	35.71	35.79	16.98	18.73
	TH-DZK-I	-43.4	-44	-20.04	-25.56
	TH-DZK-II	-43.4	-43.96	-20.04	-25.49
TH	TH-TQ	39.69	39.59	26.62	23.52
	TH-DZK-I	43.68	44.04	20.7	25.91
	TH-DZK-II	43.68	44.16	20.7	25.86
	DJ-TH-I	-63.16	-63.65	-29.54	-34.34
	DJ-TH-II	-64.69	-65.12	-29.95	-34.78
YDQ	YDQ-GM	0.74	0.92	-10	-9.5
	YDQ-MY	80.13	80.33	31.55	28.78
	YDQ-TP	73.76	74.1	35.22	39.47
	YDQ-DJ-I	-77.66	-78.12	-33.96	-35.28
	YDQ-DJ-II	-77.85	-77.86	-34.07	-35.26
DJ	YDQ-DJ-I	77.76	77.93	31.9	29.74

	YDQ-DJ-II	77.96	77.77	31.98	29.82
	DJ-TH-I	63.33	63.42	27.76	29.37
	DJ-TH-II	64.87	65.11	28.3	30.06
FJ	FJ-LB	9.9	9.79	2.92	0.79
	FJ-MY	-67.16	-67.57	-25.13	-21.8
	FJ-SY	18.27	18.07	10.2	9.31
MY	FJ-MY	68.33	67.96	28.43	25.17
	YDQ-MY	-78.75	-79.18	-27.74	-25.63
TQ	TH-TQ	-39.42	-39.25	-27.4	-25.55
WKS	WKS-DZK	-10.37	-10.72	-4.29	-6.63
HQ	HQ-DZK	-35.58	-35.76	-18.27	-21.66
GM	YDQ-GM	-0.73	-1.1	9.61	8.33
LB	FJ-LB	-9.89	-9.98	-3.06	-1.38
SY	FJ-SY	-18.2	-18.34	-10.22	-9.79
TP	YDQ-TP	-72.28	-72.96	-30.88	-35.69

Table 4 Comparison of data before and after the load active/reactive state estimation

Substation ID	Load	Active power(MW)	Active power before calculation(MW)	Reactive power(MVar)	Reactive power before calculation(MVar)
DZK	LOAD-DZK10	41.44	42.62	17.37	20
WKS	LOAD-WKS10	10.66	11	4.11	6.2
TH	LOAD-TH10	35.76	35.7	16.39	19.2
TQ	LOAD-TQ10	39.26	40	23.44	23.4
GM	LOAD-GM35	0.86	0.49	-1.02	0.29
SY	LOAD-SY10	18.2	18.37	8.72	7.83
LB	LOAD-LB10	9.87	9.71	8.05	5.14
MY	LOAD-MY10	10.63	10.6	6.57	5.65
FJ	LOAD-FJ35	38.84	36.5	22.18	20.76
TP	LOAD-TP35	62.44	62.2	33.27	33.53
TP	LOAD-TP10	10.24	10.13	3.15	5.42

Table 5 The transformer active/reactive state estimates before and after comparison

Substation	Winding name	P-measure (MW)	P-calculation (MW)	Q-measure (MW)	Q-calcuation (MW)
TH	TH1#-H	64.48	64.2	34.51	29.75
	TH1#-L	-0.26	0	9.18	9.38
	TH1#-M	-64.11	-64.65	0	-33.54
	TH2#-H	64.3	64.2	34.4	29.75
	TH2#-L	-0.41	0	9.18	9.38
	TH2#-M	-64.08	-64.61	0	-33.54
YDQ	YDQ1#-H	86.49	86	38.98	37.82
	YDQ1#-L	0.46	0	0.27	0
	YDQ1#-M	-86.5	-86.85	-32.7	-32.16
	YDQ2#-H	69.44	69.63	31.48	30.24
	YDQ2#-L	-0.6	0	-0.11	0
	YDQ2#-M	-69.13	-69.68	-26.04	-25.11
DZK	DZK1#-H	14.39	14.37	9.01	6.73
	DZK1#-L	-14.39	-14.35	-7.75	-6
	DZK2#-H	12.62	12.75	7.88	6.01
	DZK2#-L	-12.6	-12.73	-6.88	-5.36
	DZK3#-H	14.39	14.37	8.94	6.73
	DZK3#-L	-14.38	-14.35	-7.76	-6
WKS	WKS1#-H	5.24	5.32	3.24	2.12
	WKS1#-L	-5.21	-5.31	-2.94	-2.05
	WKS2#-H	5.49	5.35	3.3	2.13
	WKS2#-L	-5.2	-5.34	-2.95	-2.06
HQ	HQ1#-H	17.76	17.91	10.67	9.12
	HQ1#-L	-18.01	-17.88	-9.71	-8.2
	HQ2#-H	17.63	17.91	10.57	9.12
	HQ2#-L	-18.07	-17.88	-9.79	-8.2
TQ	TQ1#-H	19.89	19.76	13	13.76
	TQ1#-L	-19.89	-19.71	-10.6	-11.76
	TQ2#-H	19.75	19.6	12.94	13.66
	TQ2#-L	-19.63	-19.55	-10.77	-11.68
GM	GM-H	0.42	0.82	-8.57	-9.62
	GM-L	-0.22	0	8.95	9.03
	GM-M	-0.42	-0.86	-0.45	1.02
SY	SY-H	18.39	18.23	9.8	10.21
	SY-L	-18.29	-18.2	-7.81	-8.72

LB	LB1#-H	4.95	4.94	0.64	1.51
	LB1#-L	-4.93	-4.94	-0.18	-1.49
	LB2#-H	4.95	4.94	0.63	1.51
	LB2#-L	-4.93	-4.94	-0.17	-1.49
MY	MY1#-H	5.12	5.04	-0.01	0
	MY1#-L	-5.09	-5.04	0.42	0
	MY2#-H	5.68	5.6	-0.02	0
	MY2#-L	-5.65	-5.6	0.42	0
FJ	FJ1#-H	19.55	19.5	5.23	6
	FJ1#-L	-0.27	0	5.92	6.06
	FJ1#-M	-19.39	-19.42	-10.61	-11.09
	F2#-H	19.56	19.5	5.12	6
	FJ2#-L	-0.59	0	5.78	6.06
	FJ2#-M	-19.41	-19.42	-10.85	-11.09
TP	TP1#-H	62.61	62.57	33.18	31.24
	TP1#-L	0.14	0	6.98	7.79
	TP1#-M	-62.29	-62.44	-33.56	-33.27
	TP2#-H	10.28	10.25	2.07	0
	TP2#-L	-10.29	-10.24	-1.92	0.58

5.Conclusion

This article briefly describes the mathematical model of state estimation module for the advanced application the grid automatic voltage control (AVC) software. The key issues for the module in the actual operation production process are analyzed and discussed, which includes the network modeling and model validation, pretreatment process, bad data detection and identification methods. And the practical debugging method is proposed to increase the estimation pass-rate. The state estimation results obtained from the actual power system show that the systematic state estimation debugging method is reasonable and effective, which provides a technical basis and practical method for the commissioning and maintenance of system estimation for the AVC system.

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