FIELD TESTING OF DISTRIBUTION STATE ESTIMATOR

Nenad KATIC
University of Novi Sad, Serbia
nenad.katic@schneider-electric-dms.com

Li FEI
University of EST, China
lfee@163.com

Goran SVENDA
University of Novi Sad, Serbia
svenda@uns.ac.rs

Zhou Yongji
Guizhou Guangsi, China
zyj5196@qq.com

ABSTRACT

State Estimator is the basic functionality necessary for the "smart" operation of power networks, both in transmission and distribution side. Being integrated in a power management system and facing different quality of network data, robustness and efficiency are essential to provide accurate estimation of a power network operation state. Distribution State Estimator, applied in Distribution Management System development project in Guizhou Province in China, was tested in field operation. Estimation principles and test results are described in this article.

Keywords: *State Estimation, Distribution Management System*

1. INTRODUCTION

Smart operation of power distribution network requires real-time system for Supervisory Control and Data Acquisition (SCADA) integrated with Distribution Management System (DMS) for network modeling, calculation, analysis and optimization. Distribution State Estimator (DSE) is a critical pre-condition for accurate insight into the operation state of distribution network (DN) [1-5]. Since all other DMS functions depend on the quality of network state estimation, it is obvious that DSE is the basic function of DMS. DSE theory and modeling was subject of many articles, but it is hard to find experiences with application in field [6]. There were many attempts to apply state estimation models, successfully verified in transmission networks [7], also in distribution networks, however without success. The basic problem was insufficient number of real-time telemetered measurements and *non-observable* areas of distribution network [8]. To overcome such problem, robust and efficient DSE was developed, as briefly described in Section 2. Accuracy of such State Estimator was tested in several examples of the network operation in Guizhou Province in China and compared with similar testing made in European network [6]. Test results are presented and commented in Section 4, followed by conclusion and references used in writing this paper.

2. STATE ESTIMATION PROCEDURE

Distribution State Estimation procedure provides calculation of the network operation state in real-time, or for simulation analysis. It requires voltage vectors for each network *root*, network model (parameters and connectivity), available real-time data (telemetered measurements and switchgear statuses) and *virtual measurements* of non-observable areas. The measurements could be voltage magnitudes, current magnitudes, power factors, active and reactive powers at any network location.

At every network loading point without real-time measurement, appropriate virtual measurements need to be established, based on historical data:

(i) Daily load profiles (DLPs) for current magnitude and power factor or active and reactive power, normalized by average or peak values.

(ii) Load weights (LW): peak values based on field (local) measurements (A, kW, kVAr), averages derived from supplied energy (kWh, kVARh) or only rated powers of the equipment (kVA).

DLP (currents or powers) multiplied by corresponding load weight at any moment, gives corresponding absolute units (*virtual measurements* or *pseudo-measurements*). Typical DLPs are established for different consumption types (residential, commercial, industrial, etc.), furthermore, each consumption type is presented with a set of DLPs and corresponding LWs. Appropriate DLPs and corresponding LWs are established for each weather season (summer, fall, winter, spring, etc) and each typical loading day (working day, Saturday, Sunday, holiday, etc). DLPs and LWs are calculated automatically with statistical data processing of local measurement data (e.g. smart meters) or generated manually based on engineering experience.

DSE algorithm includes 4 steps [6]: (1)Pre-estimation, (2)Topology and Measurements Verification, (3)Load Calibration and (4) Load Flow Calculation.

2.1 Pre-estimation

The first step is *Pre-estimation,* which consists of Load Flow Calculation in considered time moment [9], for specified root voltage and loading values received from virtual measurements. All calculated values in this step are termed *pre-estimated values*. If power network doesn't have any real-time measurements, provided by SCADA system, this step is the last step of the estimation algorithm.

2.2 Verification

The second step is *verification,* which consists of topology (switchgear statuses) verification and real-time measurements verification.

Topology Verification includes detection and elimination of errors made in updating of the network model topology, after changes of switchgear statuses in field. Changes made by SCADA are automatically transferred to the network model, but manual operations in the field have to be updated in the model manually. Heuristic rules are used in Topology Verification process, for example, if feeder breaker is closed and there is a significant difference between SCADA real-time measurement and virtual measurements, probably an error exists in the network topology.

Measurements Verification is detection of errors in real-time measurements of SCADA system and correction to values optimally fitting the network model and virtual measurements (final estimated values). Pre-estimated values (voltages, currents, powers…) are available for any network point after DSE *pre-estimation* step, thus creating redundancy between any real-time measurement and appropriate pre-estimated value. Measurements Verification is based on this redundancy and includes five sub-steps:

(a) *Preparation of measurements:* This sub-step consists of transformation of all real-time measurements of different nature (powers, currents, power factors) into uniform measurements: 1 – current magnitude and power factors or 2 – active and reactive powers.

(b) *Elimination of obviously bad SCADA real-time measurements:* (i) it is outside of limits imposed by relay protection which has not tripped; (ii) it is zero-valued, but downstream of this measurement a load exists; (iii) it exceeds the pre-specified difference from pre-estimated value. These measurements are discarded from the next steps of the estimation procedure.

(c) *Network reduction:* In this sub-step the network is reduced by equalizing of all *non-observable islands*, which consists of all electrically connected elements (line sections, transformers …) without telemetered measurements of currents and powers. Non-observable island is connected to the external network exclusively by branches with telemetered measurements, and they are observable by their total load. In this way, after applying a very simple equivalency procedure, the predominantly non-observable network with N buses (Fig.1a) is reduced to a fully observable equivalent network with N_o buses (islands are stressed by dashed lines in Fig. 1b).

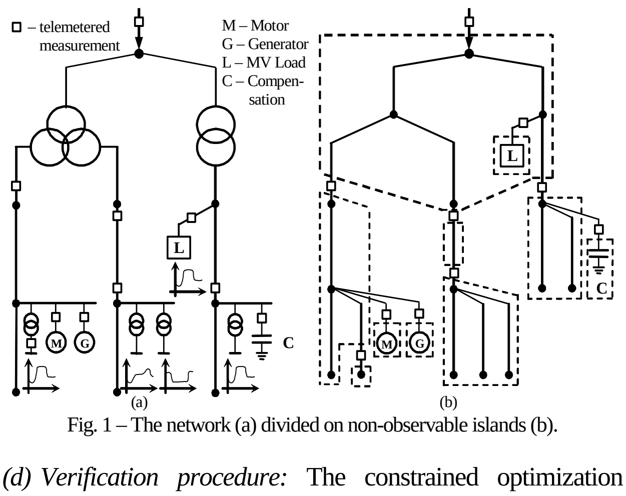

Fig. 1 – The network (a) divided on non-observable islands (b).

(d) *Verification procedure:* The constrained optimization procedure for verification of measurements, applied on the observable network equivalent model (with reduced number of buses), is radically faster than one applied on the total network model. This procedure consists of minimization of the objective function (Φ), which is the sum of weighted squares of differences between measured (m) and pre-estimated (p) from estimated values (e), of N_m telemetered measurements (x_j) and N_o total islands loads (x_n):

$$\Phi = \sum_{j=1}^{N_m} [w_j^m (x_j^m - x_j^e)^2 + w_j^p (x_j^p - x_j^e)^2] W_j + \sum_{n=1}^{N_o} [w_n^p (x_n^p - x_n^e)^2] W_n \, , \tag{1}$$

with one constraint per each island:

$$f_n = x_n^e + \Delta x_n^p - \sum_{j=1}^{N_m} k_{n,j} \cdot x_j^e = 0, \quad n = 1,... N_o \, . \tag{2}$$

The relative weights of telemetered and pre-estimated values are denoted with w; the relative weights of state variables and islands loads are denoted with W; $k_{n,j}$ represents the sign of the measured value x_j (positive when the measured value enters into the island); Δx_n represents the total active and reactive losses when active and reactive powers are the unknown variables x_j in (1) and real and imaginary parts of island total shunt current when currents are unknown variables. The results of the optimization procedure consist of *estimated measurements* and *total islands loads* that will be checked in the following sub-step.

(e) *Bad data detection and elimination:* The measurement with maximal deviation from its estimation calculated in the previous sub-step, exceeding the pre-specified threshold, is also termed *bad measurement* and it is eliminated from the remaining part of the estimation procedure. After elimination of the bad measurements, sub-steps *(c)* and *(d)* are repeated until no bad measurement exists.

2.3 Load calibration

All telemetered measurements are verified in the previous *verification step*, with result of the final *estimated* values, which have the best fit with the network model, real-time and virtual measurements. In *Load Calibration* step, all pre-estimated (non-telemetered) loads in non-observable islands are corrected (calibrated) with correction parameter, based on estimated value for an island. The estimation of the load of bus i, in the island n, with N_n buses, says:

$$x_{n,i}^e = \frac{x_n^e}{x_n^p} \cdot x_i^p, \quad i = 1...N_n, \quad n = 1,..., N_o \, . \tag{3}$$

2.4 Load-Flow Calculation

Finally, after all real-time measurements are verified and all loads estimated (calibrated) in previous steps, the operation state of the power network is recalculated with Distribution Load Flow [9]. The whole process is fully automated and takes less than second in advanced systems.

3. FIELD TESTING OF STATE ESTIMATOR

DSE was tested in a real-life operation of Distribution Utility Guizhou Power Corporation (GPC), China, Liupanshui Power Supply bureau. GPC supplies 40 million people in central Chinese province Guizhou and has implemented China's first advanced DMS in 2009–2011 [10].

Test procedure included recording of real-time measurements data, provided by SCADA system implemented on Substations 110/10 kV and by TTU system (transformer terminal units) implemented on secondary of substations 10/0,4 kV (Fig. 2), each hour in duration of 5-7 days (working days and weekend).

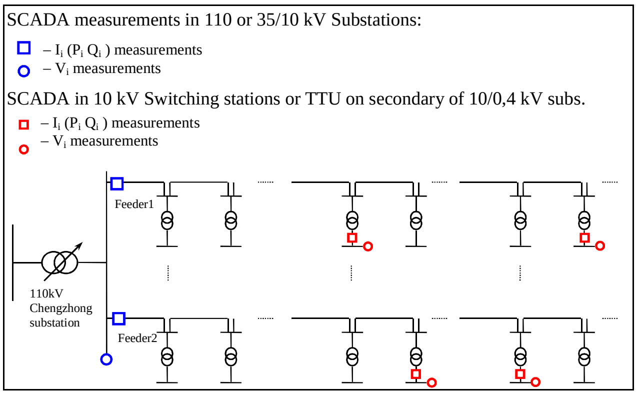

Fig. 2 – Test recording of real-time measurements data

In the same period, DSE results were recorded including *pre-estimated* values, as result of pre-estimation calculation step, and final *estimated* values, as result of verification and load calibration step, described in DSE procedure in chapter 2.

The first test was executed in May, 2012 [11] in duration of 5 days, and the second test in December 2012 in duration of seven days. Test results are presented in Figures 3 – 6, with the same line coloring: (i) *green* color for "pre-estimated" values (virtual measurements); (ii) *red* color for "estimated" values (after verification and calibration); (iii) *blue* color for real-time measurements by field devices (SCADA and TTU).

DSE estimation error [6, 11] was calculated and presented with four parameters: A – average absolute deviation of the *measured* value from *pre-estimated* [%]; B – maximal absolute deviation of the *measured* value from *pre-estimated* [%]; C – average absolute deviation of the *measured* value from *estimated* value [%]; D – maximal absolute deviation of the *measured* value from *estimated* value [%].

Test on transformers 10/0,4 kV

The transformer (LuYuan housing estate No.2 Tin kiosk) has residential load profile (Fig. 3), parameter A was 24% in pre-estimation step and parameter C 16% after calibration by DSE [11]. Pre-estimated values (green) were based on good load profile and higher peak indicator giving overestimated results; however, after verification with real-time data, final (red) estimated values were closer to reality. In this case, peak indicator should have been corrected on lower values.

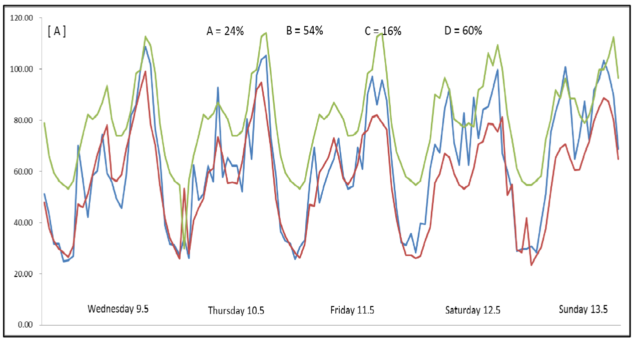

Fig. 3 – Transformer with residential load profile – LuYuan housing estate No.2 Tin kiosk

Another transformer (Local tax Bureau estate No.1) has mixed residential and commercial load profile (Figure 4), parameter A was 21% and parameter C 23%. Pre-estimated values (green) were based on good load profile and peak indicator, but due to lower temperatures than usually in December, real-time values (blue) were higher in peak-periods. Final estimation (red) was calibrated only by lower deviations on Feeder side, since there were no real-time measurements inside 10 kV feeders. More real-time (SCADA) measurements inside Feeder 10 kV would help DSE to pick-up such local changes.

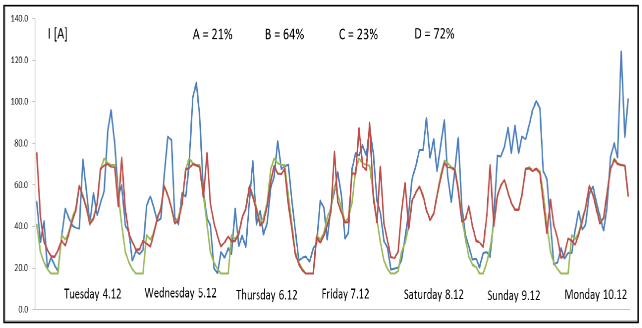

Fig. 4 – Transformer with mixed residential and commercial load profile – Local tax Bureau estate No.1

In European network [6] results were much better (A and C under 1%), since this network was tuned for many years with high improvement of load profiles.

Test on Feeders 10 kV

Feeder Zhongkang I supplies a group of six residential distribution substations, with residential load profiles assigned to each transformer (Fig. 5). Parameter A was 35% and parameter C 12%. Obviously, load profiles were overestimating night load and evening peaks, but matching good in daytime, which indicates that peak indicators were correct. In this case, load profiles should have been improved on better shape. However, after verification with real-time data, final (red) estimated values were close to reality, which presents robustness of DSE.

Feeder ZhongMing II supplies 25 residential distribution substations, with appropriate load profiles assigned to each transformer (Fig. 6). Parameter A was 23% and parameter C was 14%. Due to lower temperatures than usually in December, real-time values (blue) were higher in peak-periods, and DSE made a good calibration on working days. However, when differences between SCADA and pre-estimated values were too high (daytime in weekend) and over set limit, DSE was discarding SCADA and accepting pre-estimation. In this case, when weather conditions are deviating very much from usual in certain season, DSE verification should have been blocked and SCADA values accepted as correct.

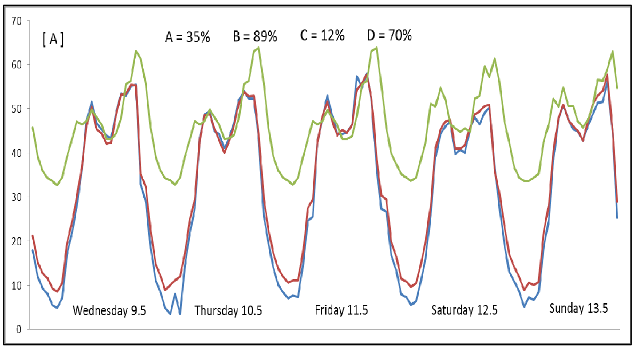

Fig. 5 – Feeder Zhongkang I with 6 residential substations

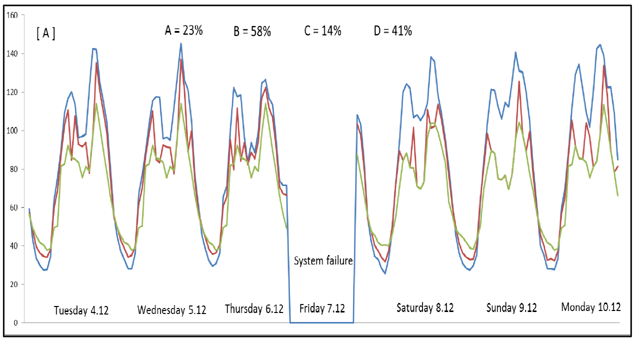

Fig. 6 – Feeder ZhongMing II with 25 residential substations

Test results presented that DSE was facing different problems in operation; however robustness of DSE algorithm was managing to reduce deviations on acceptable values. Parameter C, relevant for quality of Load flow calculation, was kept inside 10 - 20%, which is still acceptable for good results of DMS fault management and optimization functions. On the other side, continuous improvement of load profiles, better setting of peak indicators, and implementation of more real-time measurements inside 10 kV network, would significantly improve DSE results, as achieved in European network [6].

4. CONCLUSION

DSE field testing results in real power network in China were leading to the following conclusions:

a) The real-time State Estimation in distribution networks is feasible, sufficiently reliable and accurate for the purpose of real-time management of distribution networks.
b) Contribution of real-time measurements in DSE verification and calibration steps have significant impact on the quality of the DSE results, therefore more real time measurements should be available inside 10 kV network;
c) Even if a quality of historical data (load profiles) is not very high, DSE calibration based on real-time data was correcting estimated values close to real values;
d) Comparing DSE field results after short time of application in immature project in China with mature project in Europe [6], results are of expected quality;
e) Accuracy of DSE can be improved with continuous improvement of quality of historical data, based on load profiling, data clustering, post-estimation analysis, etc.

Acknowledgments

DSE was developed and put into operation by Telvent, today Schneider Electric, as part of the DMS Development project [10] in Guizhou Power Corporation, China, 2009 – 2011.

5. REFERENCES

[1] I.Roytelman; S.M.Shahidehpour: State Estimation for Electric Power Distribution Systems in Quasireal-time Conditions; *IEEE Trans. on PWRD*, Vol. 8, No. 4, October 1993, pp. 2009-2015
[2] M.E.Baran, A.W.Kelley: A Branch-Current-Based State Estimation Method for Distribution Systems; *IEEE Trans. on PS*, Vol. 10, No. 1, 1995, pp. 483-491
[3] C.N.Lu, J.H.Teng, W.-H.E.Liu: Distribution System State Estimation; *IEEE Trans. on PS*, Vol. 10, No. 1, February 1995, pp. 229-240
[4] K.Li: State Estimation for Power Distribution System and Measurement Impacts; *IEEE Trans. on PS*, Vol. 11, No. 2, May 1996, pp. 911-916
[5] A.K.Ghosh, D.L.Lubkeman, R.H.Jones: Load Modeling for Distribution Circuit State Estimation; *IEEE Trans. on PWRD*, Vol. 12, No. 2, April 1997, pp. 999-1005
[6] Z.Simendić, V.Strezoski, G.Svenda: In-Field Verification of the Real-Time Distribution State Estimation; *CIRED 18th International Conference on Electricity Distribution*, Turin, Session No. 3, 6-9 June 2005.
[7] D.Sirmohammadi, H.W.Hong, A.Semlyen, G.X.Luo: A Compensation-Based Power Flow Method for Weakly Meshed Distribution and Transmission Networks; *IEEE Trans. on PS*, Vol. 3, No. 2, May 1988, pp. 753-762
[8] M.K.Celik, W.-H.E.Liu: A Practical Distribution State Calculation Algorithm; *Proceedings of IEEE Winter Meeting '99*, New York, NY, pp. 442-447
[9] F.C.Schweppe, J.Wildes: Power System Static-State Estimation, Part I, II, III; *IEEE Trans. on PAS*, Vol. PAS-89, No. 1, January 1970, pp. 120-135.
[10] L.Fei, L.Sixi, Z.Qing, Z.Jongji: Smart Distribution, Guizhou Power Grid Co. deploys China's first advanced distribution management system; *Transmission&Distribution*, November 2012, pp. 40 – 48.
[11] N.Katic, L.Fei, G.Svenda, Z.Jongji: Distribution State Estimation Field Testing; *CICED (CIRED China) 5th International Conference on Electricity Distribution*, Paper FP0647, Shanghai, 5-6 September 2012.