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A Regularized Approach for Solving Ill-Conditioned State Estimation of Distribution Systems

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Abstract. The paper proposes new regularization method to state of the power system based on a Weighted Least-Squares (WLS) problem. The conventional WLS state estimator includes an iterative process using the Normal Equations (NE). In many cases, the NE approach is unstable and very sensitive to erroneous data. Morever, the recent trend of employing the state estimation for a distribution system has added new challenges to the numerical stability of the state estimator due to the configuration specifics of a particular distribution grid and the high *R*/*X* ratios of their feeders. Thus, the state estimator is found to be an ill-conditioned system that may fail to provide the required solution. Hence, using the proposed regularization method solves the ill-conditioning problem of the distribution system state estimation., the performance of the proposed method is evaluated based on a simulation test using the U.K. 12-bus and IEEE 14-bus systems

Keywords: Ill-conditioning, Measurement Jacobian, Regularization, *R/X* ratio, State Estimation

Pristop k ocenjevanju stanja slabo pogojenih elektroenergetskih sistemov

V prispevku je predstavljena metoda za ocenjevanje stanja elektroenergetskega omrežja na podlagi metode uteženih najmanjših kvadratov (UNK). Navadno metode UNK za ocenjevanje stanja temeljijo na iterativnem postopku, ki pa je v določenih primerih nestabilen in občutljiv na napake. Specifične konfiguracije omrežja so nov izziv pri ocenjevanju stanja, saj je lahko ocenjevanje v slabo pogojenem elektroenergetskem sistemu nepravilno. Predlagano ocenjevanje slabo pogojenih elektroenergetskih sistemov smo preverili v postopku simulacije z vodiloma U.K. 12 in IEEE 14.

1 INTRODUCTION

The power-system state estimation is an essential activity for maintaining the system operation and avoiding regional blackouts. This process is implemented in power-system control centers using the Energy Management System (EMS) and the Distribution Management System (DMS). The state of any power system, which includes voltage magnitudes and phase angles of the system buses, can be estimated as a result of solving the state estimation problem [1].

The power-system state estimator receives telemetered measurements from different locations in the power system for calculating the state vector. The real-time measurement set includes: voltage magnitudes, active and reactive power flows in each branch, active- and reactive-power injection in buses, currents of lines or branches, circuit-breaker status (on/off), and transformer tap positions. The solution of the state estimation is delivered to EMS and DMS to be utilized by other applications such as the contingency analysis and economic dispatch [1],[2]. As the measurements contain errors and noise rates, they must be processed by the state estimator using an iterative Weighted Least Square (WLS) problem [3]. This matrix-based system can be unstable numerically. This means small errors in the collected data may create substantial deviations in the estimated states. Hence, such state estimator is declared as an ill-conditioned estimator.

In large-scale power system, serious stability problems can be developed if the state-estimation monitor fits inaccurate state-estimation (i.e. the voltages and their phase angles). This problem should be intensively investigated because "If the system is ill-conditioned, then no amount of effort or talent used in the computation can produce an accurate answer except by chance" [4]. The previous statement indicates the weaknesses threaten the whole process of the power-system state estimation [5].

The paper briefly discusses the reasons of ill-conditioning in the state estimation using alternative solution methods [6, 7]. Most of these methods have been developed for the transmission systems (i.e. high-voltage grids) [8]. To use state-estimation techniques, the modern distribution systems with their radial configuration and smart meters must stand-alone. Unlike those of the transmission systems, power lines of the distribution systems have high *R/X* ratios and insufficient power measurements [9]. These characteristics negatively affect the performance of the

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WLS state estimator. Hence, the regularization approach proposed in this paper addresses the problem of ill-conditioning. Unlike the traditional regularization methods, the proposed method directly treats the Jacobian matrix.

Section 2 providres a mathematical formulation of the WLS state estimator. Section 3 describes the reasons for ill-conditioning considering the status of the power systems. Section 4 presents the proposed technique and the required process for regularizing the NE approach. Section 5 discussed the simulation tests used to evaluate the performance of the proposed method using the U.K. 12-Bus and IEEE 14-bus systems. Section 6 draws conclusions.

2 STATE ESTIMATION FORMULATION

Installing all the required types of the measuring device in all the system buses is not economically feasible. Therefore, in the state estimation, the available set of measurements is used to estimate the state of the power system [1], [2]. If a measurement set is sufficient to provide a unique solution for the state vector, the system is considered to be observable [10].

With a state vector (x) and a measurement set (z), the formula of the state estimation is [11]:

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

where $h(x)$ is nonlinear vector function and e is the error or the noise vector.

Minimization of the objective function $J(x)$ results in the WLS state estimation.

$$J(x) = (z - H(x))^T W(z - H(x)) \tag{2}$$

where $H(x) = \partial h(x) / \partial x$ is the measurement Jacobian matrix and W is the weighting factors matrix. The W matrix contains the inverse of the measurement variances, i.e. ($W = [\sigma_1^{-2}, \sigma_2^{-2}, \cdots, \sigma_m^{-2}]$). The Jacobian matrix is constructed from several blocks to form an ($m\times n$) matrix, where m is the measurements and n is the number of the state variables. For the sake of simplicity, the symbol H replaces $H(x)$. Each block of the H matrix corresponds to a specific type of the measurement as shown in (3).

$$H = \begin{bmatrix} 0 & \frac{\partial |V|}{\partial V} \\ \frac{\partial P_{inj.}}{\partial \theta} & \frac{\partial P_{inj.}}{\partial V} \\ \frac{\partial Q_{inj.}}{\partial \theta} & \frac{\partial Q_{inj}}{\partial V} \\ \frac{\partial P_{flow}}{\partial \theta} & \frac{\partial P_{flow}}{\partial V} \\ \frac{\partial Q_{flow}}{\partial \theta} & \frac{\partial Q_{flow}}{\partial V} \end{bmatrix} \tag{3}$$

The objective function can be minimized in the following manner to produce estimated state vector $\hat{x}$ (3, 10):

$$\hat{x} = (H^T W H)^{-1} H^T W z = G^{-1} H^T W z$$

where $G = H^T W H$ is the gain matrix of the WLS state estimator and the coefficient matrix of the state vector.

Then, $\Delta\hat{x}$ is the difference between true value x and estimated value $\hat{x}$ is computed as:

$$G(x^k)\Delta\hat{x}^k = H^T(x^k) W \Delta z^k \tag{4}$$

The above equation is the NE, which is solved iteratively for $\hat{x}$. This means the Jacobian H and the G matrices are repeatedly constructed at each iteration [2]. The G matrix must be sparse and invertible for obtaining the state estimation solution from (4). However, the problem of ill-conditioning can be affected by round-off errors introduced while forming the gain matrix [3], [8]. Thus, the poor conditioning originates from the Jacobian matrix, and thereby, the ill-conditioned state estimator can be predicted by examining the H matrix. On the other hand, the Jacobian measurement matrix becomes ill-conditioned if it is a rank-deficient matrix. The well-conditioned Jacobian matrix is a full-ranked matrix with its rank equaling the number of the state variables (n) [3], [10].

3 ILL-CONDITIONING: PROBLEM AND SOLUTIONS

The numerical stability of the WLS state estimation is affected by several situations that can affect the accuracy and the numerical stability of power system state estimator [2].

The state estimator is sensitive to virtual measurements and the power injections utilized to address the measurement deficiency [3], [11], [12]. The consequences of such case include the situation of a badly-scaled Jacobian matrix. However, this problem can be noticed in the transmission systems, not in the distribution systems.

The ill-conditioning reasons noticed in the distribution system are the lack of power measurements and high *R/X* ratio of the power feeders [13]–[15]. The lack of power measurements is here due to the dependence on the Ampere measurements. The Ampere measurements do not support the phase angle estimation, and are considered as redundant measurements [13]. However, the modern distribution grids contain Distributed Generators (DGs). Thus, the DGs equiped with active/reactive power measurements which enhance the measurement sufficiency and improve the numerical stability.

On the other hand, the Jacobian matrix of the distribution systems state estimator may deteriorate because of the high *R/X* ratios of the distribution system. This situation is common in the low-voltage grids because of the negligible reactance [15]. Accordingly, the diagonal elements deteriorate, and the diagonal dominance of the H matrix declines dramatically. In contrast, the diagonal elements dominate the Jacobian matrix of the transmission grids.

Numerous studies have been developed for solving the state estimation using relatively stable methods. Besides the several methods solving the discussed problem, most of the available methods are modifications of the traditional methods, which include the orthogonal factorization (QR) technique [16]; Normal Equation with Equality Constraints (NE/C) [17], [18]; Hatchel's matrix approach [19]; blocked formulation method [20]; and recently, the regularization techniques using the Singular Value Decomposition (SVD) [21–23].

To solve an ill-conditioned state estimator, the above approaches avoid using the gain matrix or treat the virtual measurements by reducing the filling-in which increases as a separate block that is added to the Jacobian matrix. However, these circumventing techniques have several drawbacks such as complex algorithms, large size of the alternative coefficient matrix (i.e. the matrix used instead of the *G* matrix), and an approximate solution when the Jacobian matrix becomes a rank-deficient matrix [8]. Therefore, the NE approach seems to be the simplest and the least expensive approach, but its state-estimation solution might be unstable and inaccurate. Thus, the proposed solution method employs the NE approach with a regularized Jacobian matrix to improve the stability and quality of the state-estimation solution.

4 THE PROPOSED SOLUTION METHOD

Unlike most of the available solution methods [8], the proposed method addresses the Jacobian matrix instead of the Gain matrix. The regularization in this approach utilizes the Jacobian matrix by adding a minimal positive value to its diagonal. The addition of this regularization parameter is mainly to support the diagonal elements against deterioration caused by the measurement deficiency or the *R*/*X* ratio. Our investigations show the Jacobian is more sensitive to these circumstances than the gain matrix. Thus, using the Jacobian matrix corrects the ill-conditioning of the WLS state estimator. Howevert, the following tasks need to be implemented to perforem an adjustable regularization to the state estimator:

a) Determination whether the state estimator is ill-conditioned. This task is carried out according to the condition number which is a measure of the stability/sensitivity of the matrix-based systems. The condition number of the WLS state estimator is [23], [24]:

$$\kappa(G) = \|G\|.\|G^{-1}\| \quad (5)$$

where $\|G\|$ is the norm of the gain matrix. The condition number is a unity or close to one for a well-conditioned matrix and an infinity if the *G* matrix is singular. For the κ values between the unity and infinity, the system can be unstable or ill-conditioned and, hence, the solution may diverge if there is some noise in the input data [2, 4]. In this paper, if the system has a condition number of 10^{12} or higher, is considered as an ill-conditioned system [25]. The cut-off value of 10^{12} corresponds to accuracy of 10^{-4}, which is the set threshold accuracy.

b) The values need to be selected to regularize the Jacobian matrix. The regularization parameter should be adaptable to the level of ill-conditioning, i.e. it should be impacting. On the other hand, it should be as small as possible to avoid affecting the accuracy of the state estimation solution. The lowest number that differing from zero for a double precision is 2.22×10^{-16} [25]. Thus, the regularization parameter must be much higher than this value for being impacting. The proposed parameter ($P_{regularization}$) is obtained using the SVD:

$$P_{regularization} = \lambda_{max} + eps_1 \quad (6)$$

where λ_{max} is the maximum singular value that is obtained from the SVD analysis and eps_1 is the Machine Epsilon. Only the singular values are needed from the SVD analysis.

c) Determination of the diagonals needed to be regularized. The Jacobian matrix consists of several blocks that depend on the measurement types. The Jacobian has several diagonals. However, the regularization parameter is added to the principal diagonal of the blocks affected by increasing the *R*/*X* ratio. These blocks are $\partial P_{inj.}/\partial\theta$ and $\partial Q_{inj.}/\partial V$. Other Jacobian's blocks are either affected marginally or are inaffected. To maintain the sparsity of the Jacobian matrix, the zero entries are excluded from the above process.

Accordingly, the proposed algorithm is simple and less expensive regarding in terms of memory size and computational efforts and has the following steps:

1- *Prepare the required measurement sets and the corresponding weighting factors. Set the iteration counter to k=0*
2- *Construct the Jacobian matrix H*
3- *Compute the Rank of H*
4- *If the rank is full (i.e., Rank = n) go to step 7; Otherwise,*
5- *Implement the SVD for:*
6- *Compute the maximum singular value and compute the* $P_{regularization}$
7- *Build the regularized Jacobian matrix.*
8- *Construct the Gain matrix* $(H^T WH)$
9- *Solve (5) for* Δx^k.
10- *Check the convergence rate, if* ($max|\Delta x^k| \leq tolerance\ rate$)*, stop; otherwise, continue.*
11- *Update the state vector* ($x^{k+1} = x^k + \Delta x^k$) *and the iteration counter (k=k+1), return to step 3.*

Compared to SVD, the proposed technique has only one coefficient matrix (the *G* matrix), whereas in SVD there are three. On the other hand, it is well-known that SVD delivers an approximate solution since it ignores the zero singular values.

5 SIMULATION TESTS

For evaluating the performance of the proposed solution method is power systems are used using two test cases. The first the IEEE 14-bus system with a mesh configuration is a transmission system, and second the U.K. 12-bus system is a distribution system with a weakly-meshed grid [26]. The IEEE 14-bus has low *R*/*X* ratios for its power lines, the U.K. 12-bus system has relatively high *R*/*X* ratios [27]. The configuration of the U.K. 12-bus system is shown in Fig. 1, and the details of the IEEE 14-bus system in [28].

Table I illustrates the details of the measurement sets used for the tests. The tests of the study cases are carried out using MATLAB.

Table 1. The measurement set and the redundancy of the two test systems.

Measurements	12-Bus system		14-Bus system	
	Set 1	Set 2	Set 1	Set 2
Measurements (*m*)	37	29	41	33
State variables (*n*)	23	23	27	27
Redundancy (*m*/*n*)	1.61	1.26	1.52	1.22

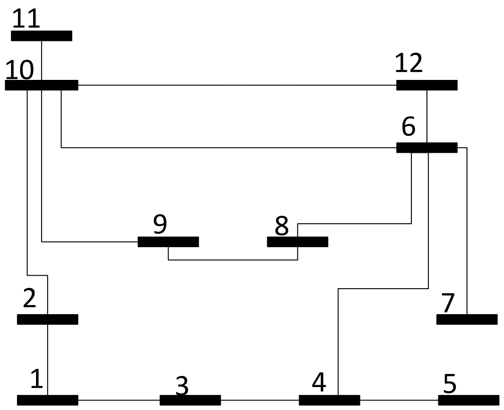

Figure 1. The test system of 12-bus weakly-meshed network.

the *R*/*X* case and the left ones represent the Jacobian matrix with a ratio of 6(*R*/*X*). The distribution grid is dramatically affected by this change while the 14-bus system is slightly affected. The reduction rate of the 12-bus distribution grid is about two thirds (65%), while

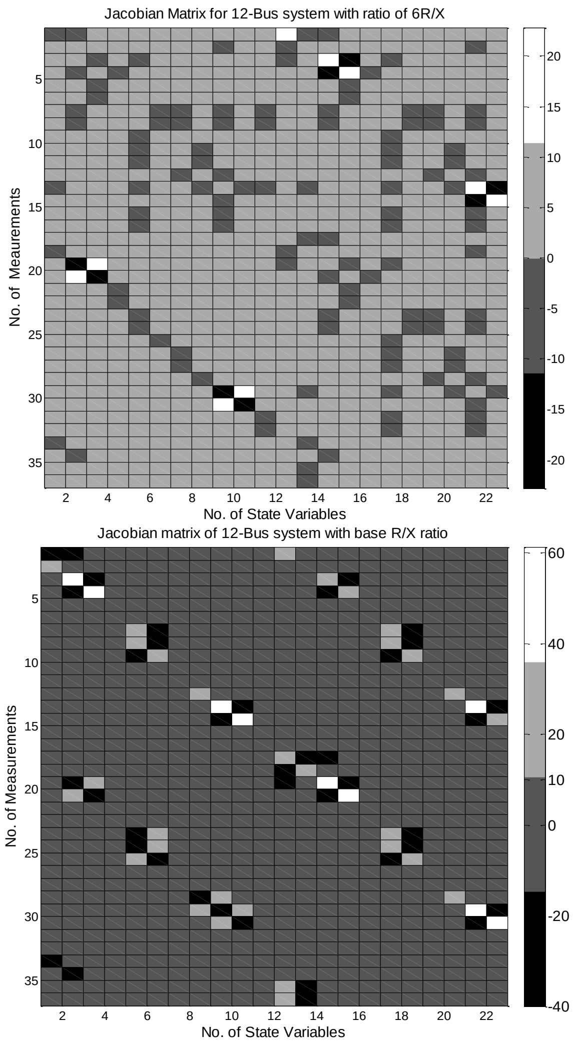

Figure 2. Jacobian matrix of 12-bus system for two *R/X* ratios.

5.1 Construction of the Jacobian matrix

The tests of the first case-study are implemented for analyzing the structure of the Jacobian matrix regarding the sparsity, diagonal dominance, and effect of the *R*/*X* ratio. Thus, the impact of the increased *R*/*X* ratio of the distribution feeders is examined. The Jacobian matrices are constructed for both the IEEE 14-bus and the U.K. 12-bus system according to the measurement sets in Table I. illustrates the construction of the Jacobian matrices of the IEEE 14-bus system and U.K. 12-bus system respectively. Then, two different *R*/*X* ratios of are used for a comparison. The patterns of the Jacobian matrices of the two test systems for two different *R*/*X* ratios are shown in Fig. 2.

Firstly, the base values of the power lines resistance (*R*) are used, then they are increased six times, 6(*R*) while keeping *X* the same. Thus, the right-side figures refer to the entries of the 14-bus Jacobian matrix are reduced to some 25% of their base values. This deterioration cannot be avoided when using the orthogonal decomposition or the SVD technique since it is related to the construction of the Jacobian matrix rather than the gain matrix.

Fig. 3 shaows that the main deterioration happen for the blocks affected by the decoupling process. i.e., the blocks represent the relations of ($P_{injection}$ $-\theta$) and ($Q_{injection}$ $-V$). These are blocks H21 and H32. In the above figures, the first quarter which represents the power measurements turns grey and the white diagonal peaks disappear to form the Jacobian structure. Thus, these changes confirm the proposed criteria for selecting the elements to be regularized.

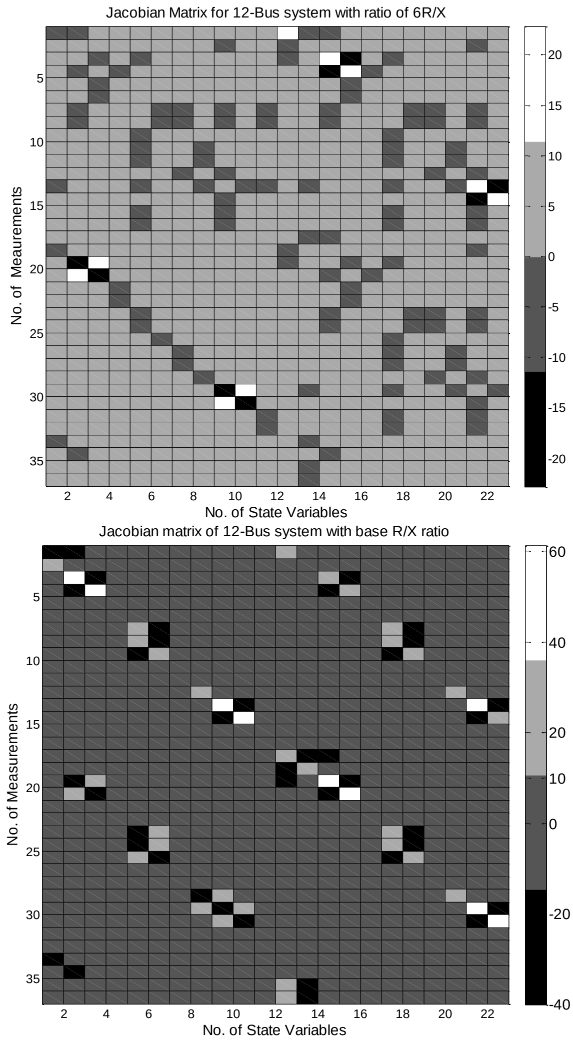

Figure 3. Jacobian matrix of 12-bus system for two *R/X* ratios.

Regarding the measurement uncertainty, the state variables (angles and voltage magnitudes) are increased at different rates for each state variable. The uncertainty values are inferred from the diagonal values of the covariance matrix (σ) that is extracted from the inverse of the *G* matrix. A confidence bound of [-3%, 3%] from the mean have been used. The following formula represents the percentage uncertainty of the state variables (E):

$$Percentage\ Uncertainty = \pm 3\ \frac{\sigma}{E} * 100$$

5.2 Measurements Deficiency

In the second case, the proposed approach is applied to two different situations: the first is when there is a sufficient number of measurements (Set 1) (Table I). The second case is for a small number of measurements, i.e. when the redundancy rate is close to the unity. Both measurement sets are illustrated in Table II. By removing the power-flow measurements, the 12-bus network depends more on the pseudo-measurements instead on the real-time measurements, which is the common situation of most distribution grids. This process enables investigating the impact of the DGs in distribution grids regarding the state-estimator stability. The regularization parameter of this test is 9.61×10^{-5}.

The condition numbers associated with each case are calculated for comparison purposes. These condition numbers are based on the regularized Jacobian matrix with the regularization parameters shown in Table II. The improvement on the conditioning level is noticed after applying the proposed method, and the effect of the measurement redundancy can be deduced by examining the condition numbers.

Table 2. Condition numbers of the test systems for the two methods and measurement sets.

Systems/ Methods		**Sets/ Condition numbers**	
		Set 1	**Set 2**
U.K 12-Bus	NE method	5.396×10^{4}	1.595×10^{21}
	Proposed method	2.327×10^{4}	1.332×10^{14}
IEEE 14-Bus	NE method	1.975×10^{5}	2.311×10^{18}
	Proposed method	2.605×10^{4}	3.951×10^{12}

6 CONCLUSION

A regularization method is proposed to solve the ill-conditioning problem of the WLS state estimator by regularizing the Jacobian matrix. It analyzes the reasons of ill-conditioning, improves the conditioning level of the test systems, and reduces the number of the required measurements for observability. The reduction in the measurements is required to add accurate meters such as PMUs. While the numerical stability of other methods is robust, the proposed method offers a simple, efficient, and stable state estimator. Moreover, it is adjustable to respond to specific features such as limited number of measurements and high *R/X* ratio of the distribution feeders. However, further investigations will be needed to use the method for an optimal PMU placement and linear state-estimation.

REFERENCES

[1] Abur, A. and Exposito, A. G. "Power System State Estimation Theory and Implementation" CRC Press, 2004.

[2] Monticelli, A., "Electric power system state estimation," Proceedings of the IEEE, vol. 88, pp. 262-282, 2000.

[3] Gu, J. W., Clements, K. A., Krumpholz, G. R. and Davis, P. W., "The Solution of Ill-Conditioned Power System State Estimation Problems Via the Method of Peters and Wilkinson," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-102, pp. 3473-3480, Oct. 1983.

[4] Rice, J. R. "Matrix computations and mathematical software" New York: McGraw-Hill, 1981.

[5] Simoes-Costa, A. and Quintana, V. H., "An Orthogonal Row Processing Algorithm for Power System Sequential State Estimation," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-100, pp. 3791-3800, 1981.

[6] Holten, L., Gjelsvik, A., Aam, S., Wu, F. F. and Liu, W. H. E., "Comparison of different methods for state estimation," Power Systems, IEEE Transactions on, vol. 3, pp. 1798-1806, 1988.

[7] Wu, F. F., "Power system state estimation: a survey," International Journal of Electrical Power & Energy Systems, vol. 12, pp. 80-87, 1990.

[8] Abood, Hatim G., Victor Sreeram, and Yateendra Mishra. "A new algorithm for improving the numerical stability of power system state estimation." IEEJ Transactions on Electrical and Electronic Engineering, vol. 14, pp. 1-8, 2018.

[9] Lu, C. N., Teng, J. H. and Liu, W. H. E., "Distribution System State Estimation," IEEE Transactions on Power systems, vol. 10, pp. 229-240, February 1995.

[10] Krumpholz, G. R., Clements, K. A. and Davis, P. W., "Power System Observability: A Practical Algorithm Using Network Topology," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-99, pp. 1534-1542, 1980.

[11] Schweppe, F. C. and Wildes, J., "Power System Static-State Estimation, Part I: Exact Model," Power Apparatus and Systems, IEEE Transection on, vol. PAS-89, pp. 120-125, 1970.

[12] Monticelli, A., Murari, C. A. F. and Wu, F. F., "A Hybrid State Estimator: Solving Normal Equations By Orthogonal Transformations," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-104, pp. 3460-3468, 1985.

[13] Tripathy, S. C., Prasad, G. D., Malik, O. P. and Hope, G. S., "Load-Flow Solutions for Ill-Conditioned Power Systems by a Newton-Like Method," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-101, pp. 3648-3657, 1982.

[14] Munoz, J. M. R. and Exposito, A. G., "A line-current measurement based state estimator," Power Systems, IEEE Transactions on, vol. 7, pp. 513-519, 1992.

[15] Li, H., Zhang, A., Shen, X. and Xu, J., "A load flow method for weakly meshed distribution networks using powers as flow variables," International Journal of Electrical Power and Energy Systems, vol. 58, pp. 291-299, 2014.

[16] Haughton, D. A. and Heydt, G. T., "A Linear State Estimation Formulation for Smart Distribution Systems," Power Systems, IEEE Transactions on, vol. 28, pp. 1187-1195, 2013.

[17] Simoes-Costa, A. and Quintana, V. H., "An Orthogonal Row Processing Algorithm for Power System Sequential State Estimation," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-100, pp. 3791-3800, 1981.

[18] Korres, G. N. and Alexopoulos, T. A., "A Constrained Ordering for Solving the Equality Constrained State Estimation," Power Systems, IEEE Transactions on, vol. 27, pp. 1998-2005, 2012.

[19] Hayes, B. P., Gruber, J. K. and Prodanovic, M., "A Closed-Loop State Estimation Tool for MV Network Monitoring and Operation," Smart Grid, IEEE Transactions on, vol. 6, pp. 2116-2125, 2015

[20] Gjelsvik, A., Aam, S. and Holten, L., "Hachtel's Augmented Matrix Method - A Rapid Method Improving Numerical Stability in Power System Static State Estimation," Power Apparatus and Systems, IEEE Transactions on, vol. PAS-104, pp. 2987-2993, 1985.

[21] Alvarado, F. L. and Tinney, W. F., "State estimation using augmented blocked matrices," Power Systems, IEEE Transactions on, vol. 5, pp. 911-921, 1990.

[22] Rakpenthai, C. and Uatrongjit, S., "Rectangular coordinates state estimation of electrical power system using singular value decomposition," in Industrial Technology, 2009. ICIT 2009. IEEE International Conference on, 2009, pp. 1-4.

[23] Abood, Hatim G., Victor Sreeram, Hassan Al-Saadi, and Yateendra Mishra. "Solution methods of Ill-conditioned power system state estimation: a comparative study." In 2017 IEEE Region 10 Symposium (TENSYMP), pp. 1-6. IEEE, 2017.

[24] de Almeida, M. C., Garcia, A. V. and Asada, E. N., "Regularized Least Squares Power System State Estimation," Power Systems, IEEE Transactions on, vol. 27, pp. 290-297, 2012.

[25] Mallik, S. K., Chakrabarti, S. and Singh, S. N., "A regularized method for solving ill-conditioned hybrid state estimation problem," in Power, Control and Embedded Systems (ICPCES), 2012 2nd International Conference on, 2012, pp. 1-6.

[26] Danna, E. J. A. and Klotz, E. S., "Determining ill conditioning in square linear system of equations," ed: Google Patents, 2014.

[27] Ahmadi, A. R. and Green, T. C., "Optimal power flow for autonomous regional active network management system," in Power & Energy Society General Meeting, 2009. PES '09. IEEE, 2009, pp. 1-7.

[28] Christie, R., "Power systems test case archive," Electrical Engineering dept., University of Washington, 2000.

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