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A NOVEL LINE FLOW BASED STATE ESTIMATION TECHNIQUE FOR POWER SYSTEMS

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ABSTRACT

A novel, line flow based state estimation (LFBSE) technique for power systems is presented in this paper. State variables are estimated through the constant, line flow based jacobian matrix constructed from the network equations. Unlike the conventional techniques where the outputs are the vectors of bus voltage magnitudes and angles, the results of the proposed method are in the terms of the quantities that indicate the line loadings and bus voltage magnitudes which can be used to identify the overloaded lines and limit violated buses instantaneously. The line flow based state estimation problem has been solved using Weighted Least Squares (WLS) technique and the results are validated against those obtained using the conventional WLS technique.

Nomeclature

LFBSE – Line Flow Based State Estimation

SE – State Estimation

WLS – Weighted Least Squares

PM – Proposed Method

z – Measurement Vector

x^0 – Initially assumed values of state vector

x_k–State vector at k^{th} iteration

x_{k+1}–State vector at $k+1^{th}$ iteration

Δx_k–State correction vector after k^{th} iteration

H - Jacibian Matrix

h(x) – Measurement function

J(x) – Objective function

v – Vector of measurement residues

$[H^T WH]$ – Gain matrix

P_i = Real bus power injection

Q_i = Reactive bus power injection

A_{ij} = ij^{th} element of bus incidence matrix

A_{ij}' = ij^{th} element of modified bus incidence matrix

P_j = Real power flow in j^{th} line

l_j = Real power loss in j^{th} line

Q_j = Reactive power flow in j^{th} line

m_j = Reactive power loss in j^{th} line

H = Diagonal matrix formed by the sum of shunt and compensating susceptances at each bus

R – Diagonal matrix of line resistances

X – Diagonal matrix of line reactances

Λ - Diagonal matrix of order 1 with the values equal to the square of the tap settings

A_{1+} and A_{1-} Positive and negative element of A_1

λ and μ - Lagranjian Multipliers

C - Loop incidence matrix

α - Phase angle of the phase shifter, taken as 1 otherwise

ΔV_{rms}, Δp_{rms}, Δq_{rms} - Root Mean Square values of the corresponding quantities

V_i^t, p_i^t, q_i^t = True values of the respective quantities on i^{th} bus

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INTRODUCTION

State estimation (SE) studies form an integral part of power system security analysis which is carried out to assess the operating state of the power system. Measurements obtained from various locations and the output of network topology processor form the inputs and bus voltage magnitudes and angles are the outputs. As the power systems keep expanding constantly and as the need to supply reliable quality power to the consumer is being stressed more in the present day competitive market based environment there is always a quest to develop new techniques which prove themselves to be efficient than the existing ones.

WLS technique has been widely used for solving the problem of state estimation (Schweppe and Wildes, 1970). Many variants of this technique are available, each working in its own way to achieve the goal of quality solution within a reasonable time frame using the available information.

A method for real time state calculation of power systems based on line flow measurements is proposed in (Dopazo *et al*., 1972) where network element voltages and bus voltages are computed alternatively until the convergence condition on bus voltages is satisfied. A fuzzy logic based weighted least squares state estimation is proposed in (Shabani *et al*., 1996) where the problem of minimizing the residuals is formulated as a multiobjective optimization problem. A fast super decoupled state estimator is suggested in (Roy and Mohammed, 1997) in which both, the vectors of measurement function and state variables are operated by a rotational operator resulting in a formulation that demands alternate iterations of active and reactive equations thereby avoiding the approximation errors due to decoupling. A WLS state estimation augmented by singular value decomposition which can yield a solution despite unobservability is suggested in (Madtharad *et al*., 2003). A Genetic Algorithm supported maximum agreement algorithm for the solution of state estimation problem is outlined in (Gastoni *et al*., 2004). Global convergence is assured through a back tracking algorithm proposed in (Pajic and Clements, 2005) where the trust region formed indicates that the algorithm is more robust than other methods.

An L_P norm based state estimation has been developed in (Logic *et al*., 2005) with a view to obtain robust solution. A QR decomposition based approach in which virtual measurements are treated as equality constraints to avoid numerical ill conditioning is explained in (Zhengchun *et al*., 2005), where triangular factorization of the coefficient matrix is performed through QR decomposition on two partitioned matrices and solution is obtained by solving a linear equation set involving a sparse triangular matrix.

An LAV approach which applies an iteratively reweighted least squares method for sequential L_1 regression is proposed in (Jabr, 2006). A modified WLS formulation which considers measurements to be dependent on one another is suggested in (Caro *et al*., 2009). A two stage phasor assisted state estimation algorithm in which at the first stage conventional WLS solves the problem and in the second stage solution quality is enhanced using current and voltage phasor measurements is presented in (Ranjana *et al*., 2010).

A new SE technique treating line flows and voltage magnitudes as state variables has been proposed in this article with a view to linearize the SE problem and to realize a constant jacobian matrix. The proposed method has been tested on three standard test systems and results obtained are presented.

Conventional WLS State Estimation

The state estimation techniques aim at finding out a set of state vectors that minimize the measurement residuals. Basically the problem is a minimization problem and as the quantities involved are nonlinear, it is a problem of minimizing a nonlinear objective function which is conveniently achieved using least squares technique. The measurements are expressed as a function of the state vector of the system as

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

Here, the measurement errors which generally show normal distribution around a zero mean are assumed to be independent of each other. Each one of the measurement is assigned a suitable weightage reflecting the accuracy and the reliability of that particular measurement. These weightages are decided based upon several factors such as the condition of the measuring equipment, noise of the telemetry channel etc.

The objective of WLS state estimator is to generate a suitable set of state variables in terms of bus voltage magnitudes and angles to minimize the weighted sum of the squares of the measurement errors, to achieve this the objective function is formulated as

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

where W is the weightage matrix , which is a diagonal matrix formed by measurement covariances when the measurements are independent of each other. The above equation is solved iteratively for estimating the state vector that minimizes J. At the end of every k^{th} iteration, the state vector is updated using the correction vector as

$$x_{k+1} = x_k + \Delta x \tag{3}$$

in which Δx obtained by solving the equation

$$\Delta x_k = [H^T WH]^{-1} H^T W[z - h(x)] \tag{4}$$

where H stands for the Jacobian and $[H^T WH]$ represents the gain matrix.

Proposed Method

The proposed method tries to solve the SE problem by applying WLS technique on a line flow based model (Yan *et al*., 2005) which is constructed using power balance equations, line voltage equations and loop phase angle equations. The general power balance equations for the system are written as

$$P(T) = e^{\frac{-\Delta F}{T_t}} \tag{5}$$

$$A.p - P_{GL} - A'.l = 0 \tag{6}$$

$$A.q - Q_{GL} - A'.m - H.V^2 = 0 \quad (7)$$

where A and A' are defined as bus incidence and modified bus incidence matrices in which all +1's in A are set to zeros, l and m represent the real and reactive power losses in the transmission lines, H is an (n-1) diagonal matrix formed by the sum of charging and compensating susceptances at each bus bar, P_{GL} and Q_{GL} are the real and reactive bus power injections, p and q are the real and reactive power flows measured at the receiving end of the transmission line. When the reactive mismatch equations are deleted at generator buses then the above equation can be rewritten as

$$A_1.q - Q_{GL}l - A_1.m - H_1.V^2 = 0 \quad (8)$$

in which H' is a diagonal matrix with only the elements corresponding to load buses present in it.

The line voltage equations are written based on a network branch model developed without taking into account the shunt elements including the line capacitances as,

$$2Rp + 2Xq - (\Lambda A_{1+}^T + A_{1-}^T)V^2 = -k + \Lambda A_C^T V_{PV}^2 \quad (9)$$

where k is the vector of apparent line losses, A_C is the bus bar incidence matrix corresponding to only the PV buses, V_{PV}^2 is the vector of the square of the generator bus voltages, Λ is the diagonal matrix of order 1 with the values equal to the square of the tap settings, A_{1+} and A_{1-} are the positive and negative element parts of A_1, R and X are the diagonal resistance and reactance matrices.

The loop phase angle equations are written based on the fact that the algebraic sum of phase angle drops around independent loops are zeros.

$$CXp - CRq = 0 \quad (10)$$

The real and reactive bus powers as a function of real line flows, reactive line flows, real line loss, reactive line loss and V_m^2 can be written as

$$P_i = \sum_{j=1}^{nl} A_{ij} \; p_j - \sum_{j=1}^{nl} A'_{ij} \; l_j \quad (11)$$

$$Q_i = \sum_{j=1}^{nl} A_{ij} \; q_j - \sum_{j=1}^{nl} A_{ij} \; m_j + H_{ii} V_i^2 \quad (12)$$

Treating p, q and V_m as state variable$[x]$, the measurement set $[Z]$ can be represented as

$$[Z] = [f(x)] \quad (13)$$

where $[Z] = [P, Q, p, q, V^2]^T$. The WLS objective function is written as

$$Min\ \varphi = [f(x) - Z]^T [w][f(x) - Z] \quad (14)$$

As the above equation does not include line capacitances and shunt susceptances, it is inadequate to estimate the system state. However the problem is made solvable by considering the constraint equations involving branch voltage drop and phase angle variations. These equations are written as

$$h(x) = 2Rp + 2Xq - (\Lambda A_{1+}^T + A_{1-}^T)V^2 = 0 \quad (15)$$

$$g(x) = CXp - CRq - C\alpha = 0 \quad (16)$$

The constrained optimization problem involving equations (14), (15) and (16) is converted into an unconstrained problem through Lagrangian multipliers λ and μ as

$$Min\ \varphi = [f(x) - Z]^T [W][f(x) - Z] - \lambda h(x) - \mu g(x) \quad (17)$$

Line arising the above equation around a known operating point x^0 , and then differentiating it and equating it to zero will result in a matrix equation of the following form

$$\begin{bmatrix} 2F^T W F & -H^T & \_G^T \\ H & 0 & 0 \\ G & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta x \\ \lambda \\ \mu \end{bmatrix} = \begin{bmatrix} -2F^T W (f(x^0) - Z) \\ -h(x^0) \\ -g(x^0) \end{bmatrix} \quad (18)$$

where F, H and G represent the jacobian matrices. These matrices are constant ones and the right hand side vector is divided into two groups, one consisting of the bus power injections and generator bus voltages which are constants and the other consisting of the loss term and charging and compensating powers which are nonlinear. So the right hand side vector is partially linearised. The algorithm for solving the objective function given in (18) is explained in the following section.

Algorithm of the Proposed Method

1. For the given network, the bus incidence matrices and matrices describing real and reactive power balance are obtained.
2. Line voltage equations which relate the bus bar voltages to the receiving end power are written in matrix form.
3. Loop phase angle equations are also written in matrix form.
4. From these matrix equations the necessary forms of A matrices, C matrix, R and X matrices which are required for the formation of jacobian matrices are extracted.
5. The left hand side matrix of equation (18) is assembled in terms of these constant jacobian matrices and the constant part of the right hand side vector is also obtained from the known quantities.
6. For the given set of measurements, the mismatch vector is calculated.
7. Equation (18) is solved and correction vector is obtained.
8. Convergence check is carried out.
9. If converged, the procedure is stopped, otherwise state vector is updated and steps 7 and 8 are repeated till convergence is attained.

RESULTS AND DISCUSSION

The proposed method has been tested on standard IEEE 14, 30 and 57 bus test systems. The measurement vector has been generated by adding a small percentage of noise to the values obtained from the Newton Raphson load flow. Bus voltage magnitudes at the load buses and real and reactive power flows through the lines were taken as state variables. All the line flows, bus power injections and bus voltage magnitudes at the even numbered buses were considered in the measurement set to achieve necessary redundancy. To study the performance of the algorithm under normal and over load conditions, it has been tested under various load factors ranging from 1.0 to 1.5 wherein the real and the reactive powers in the load bus were increased keeping the load power factor constant. The performance of the algorithm has been validated by comparing the results of the proposed method against the results obtained using standard WLS state estimation.

The algorithms were tested with a flat start and a convergence tolerance of 0.0001. Three performance indices are defined to validate the performance of the proposed technique. They are ΔV_{rms}, Δp_{rms}, Δq_{rms}.

$$\Delta Vrms = \sqrt{\frac{1}{nb}\sum_{i}^{nb}(V_i^t - V_i)^2} \qquad (19)$$

$$\Delta p_{rms} = \sqrt{\frac{1}{nl}\sum_{i}^{nl}(P_i^t - P_i)^2} \qquad (20)$$

$$\Delta q_{rms} = \sqrt{\frac{1}{nl}\sum_{i}^{nl}(q_i^t - q_i)^2} \qquad (21)$$

Tables 1, 2 and 3 compare the performance of the proposed method with WLS estimation algorithm in terms of the performance indices defined in 19, 20 and 21and NET. The performance of the algorithm is also illustrated through bar charts in Fig 1 to 12.This graphical representation has been obtained for various load factors ranging from 1.0 to 1.5.

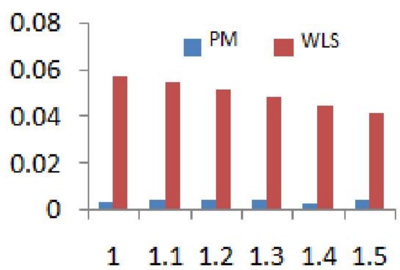

Fig.1: Load Factor vs ΔVrms

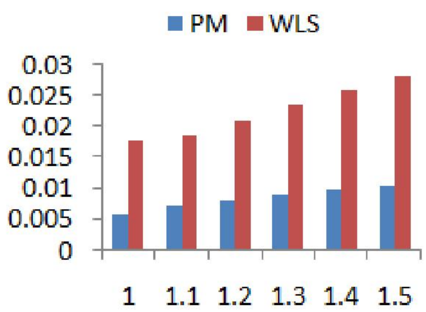

Fig.2: Load Factor vs ΔPrms

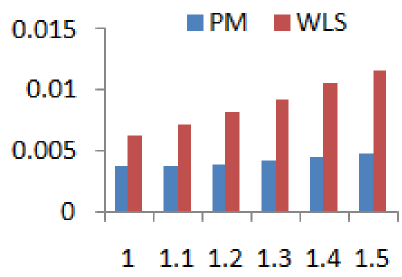

Fig.3: Load Factor vs ΔQrms

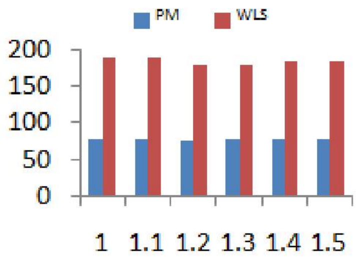

Fig.4: Load Factor vs NET

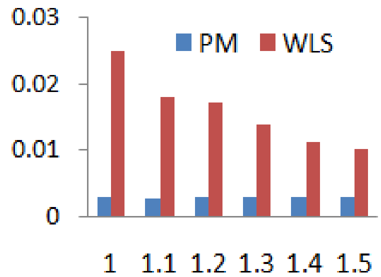

Fig.5: Load Factor vs ΔVrms

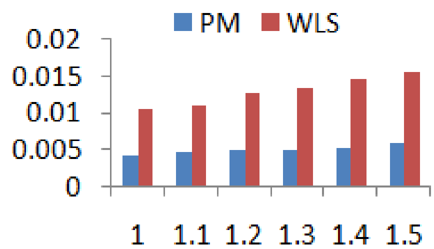

Fig.6: Load Factor vs ΔPrms

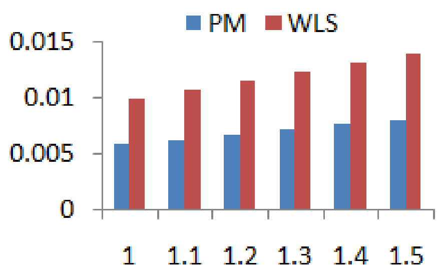

Fig.7: Load Factor vs ΔQrms

Table 1. Results for IEEE 14 Bus System

Load Factor	Proposed Method(PM)				WLS			
	ΔV rms	ΔP rms	ΔQ rms	NET (ms)	ΔV rms	ΔP rms	ΔQ rms	NET (ms)
1.0	0.0042	0.0059	0.0037	78	0.0572	0.0177	0.0062	187
1.1	0.0046	0.0073	0.0037	78	0.0543	0.0187	0.0072	187
1.2	0.0045	0.0081	0.0039	76	0.0512	0.0211	0.0082	178
1.3	0.0047	0.0089	0.0042	78	0.0481	0.0235	0.0092	179
1.4	0.0030	0.0098	0.0044	79	0.0447	0.0258	0.0105	182
1.5	0.0045	0.0106	0.0047	78	0.0414	0.0283	0.0116	182

Table 2. Results for IEEE 30 Bus System

Load Factor	PM				WLS			
	ΔVrms	ΔPrms	ΔQrms	NET(ms)	ΔVrms	ΔPrms	ΔQrms	NET(ms)
1.0	0.0029	0.0043	0.0058	97	0.0249	0.0107	0.0099	561
1.1	0.0027	0.0046	0.0062	97	0.0179	0.0112	0.0106	560
1.2	0.0029	0.0049	0.0066	94	0.0171	0.0128	0.0114	561
1.3	0.0028	0.0049	0.0071	92	0.0137	0.0137	0.0122	561
1.4	0.0028	0.0052	0.0076	92	0.0111	0.0148	0.0130	562
1.5	0.0029	0.0059	0.0079	92	0.0101	0.0158	0.0138	561

Table 3. Results for IEEE 57 Bus System

Load Factor	PM				WLS			
	ΔVrms	ΔPrms	ΔQrms	NET(ms)	ΔVrms	ΔPrms	ΔQrms	NET(ms)
1.0	0.0018	0.0190	0.0167	111	0.00923	0.0558	0.0986	1654
1.1	0.0022	0.0184	0.0178	116	0.00920	0.0551	0.0986	1685
1.2	0.0020	0.0190	0.0185	116	0.00925	0.0552	0.0986	1732
1.3	0.0020	0.0193	0.0179	125	0.00929	0.0555	0.0987	2091
1.4	0.0021	0.0199	0.0179	125	0.00926	0.0554	0.0986	2096
1.5	0.0021	0.0193	0.0178	124	0.00920	0.0555	0.0986	2096

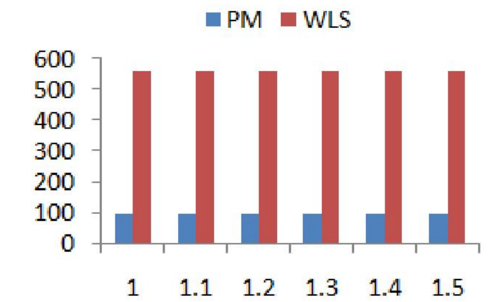

Fig.8: Load Factor vs NET

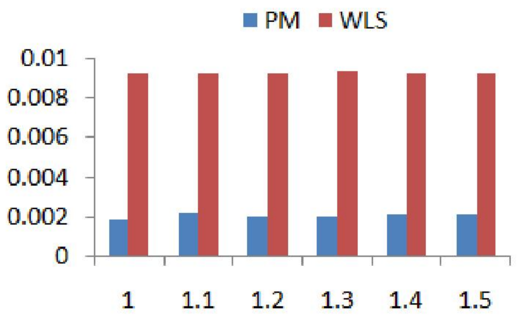

Fig.9: Load Factor vs ΔVrms

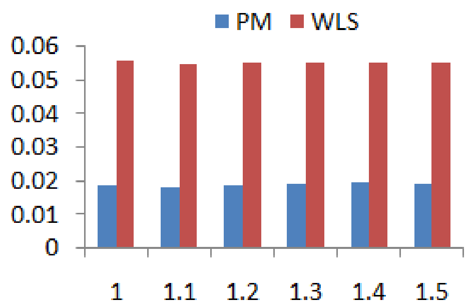

Fig.10: Load Factor vs ΔPrms

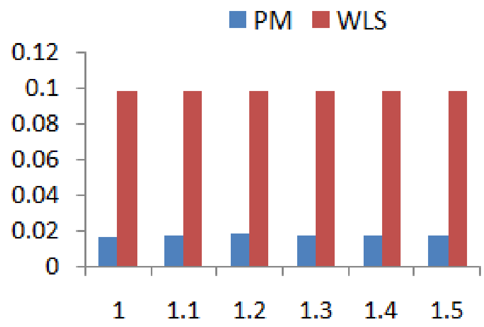

Fig.11: Load Factor vs ΔQrms

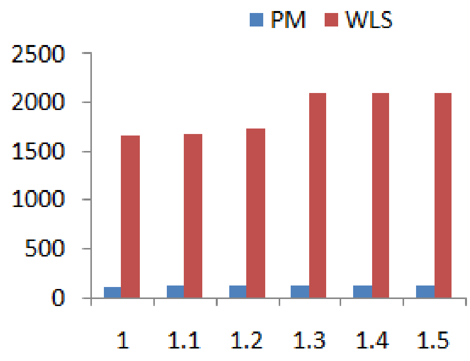

Fig.12: Load Factor vs NET

CONCLUTION

A new SE technique treating line flows and bus voltage magnitudes as state variables has been proposed in this article with a view to linearize the SE problem. The proposed method has been tested on three standard test systems and results with reasonable accuracy were obtained. The results indicate that the normalized value of the error between the actual values and estimated values of the state variables is considerably lesser in the case of proposed method than that of the conventional WLS technique. The proposed method takes lesser execution time than WLS technique as it uses a constant jacobian. A part of the right hand side vector is also constant and this part and the jacobian are to be computed only once at the beginning of the iterative procedure. The time required for execution of the proposed method and the normalized error values are compared against the corresponding values obtained by applying conventional technique in tables 1 to 3.The performance comparison of the proposed method with that of the WLS technique has also been made through bar chart representations. From these it can be understood that the proposed method based on line flows is much less time consuming and is capable of making estimates which are comparable with those obtained through conventional technique which makes it highly suitable for online procedures such as security assessment.

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