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A ROBUST LINE FLOW BASED WLAV STATE ESTIMATION TECHNIQUE FOR POWER SYSTEMS

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ABSTRACT

State Estimation techniques are widely used to estimate the operating state of power systems in the most reliable manner so that the estimated state variables reflect the current system state faithfully and these studies enable the energy management centre to operate the system in a secure manner under normal as well as contingent conditions. Those algorithms which generate a fairly good estimate in spite of the presence of bad measurements are considered to be comparatively superior and WLAV based SE has been widely accepted as one such technique whose output is almost immune to the existence of bad measurements. In this paper, a new line flow based WLAV state estimation (WLAV-LFBSE) technique for power systems using line flows and bus voltage magnitudes as state variables has been suggested. A constant, line flow based jacobian matrix has been arrived at through suitable manipulation of network equations and this technique generates an output which are in terms of quantities of real concern namely line flows and bus voltage magnitudes. As these quantities undergo wide variations due to load changes, it becomes essential to study the performance of the algorithm under varying loads. The proposed method has been tested on standard test systems taking into account these load variations and the results are analysed.

Keywords: state estimation, weighted least absolute value, line flow based WLAV, power system.

INTRODUCTION

State estimation techniques were developed for the purpose of generating a data base for power system studies from the available redundant set of erroneous measurements. In the present day circumstances where the power systems are operated under constantly growing stress, system security is under great threat and to ensure that the system operates in a secured manner even under contingent conditions, the system is to be monitored continuously and corrective actions are to be implemented to limit the out of bound voltages and to relieve the lines off their overloads. This makes it inevitable to use real time monitoring and estimating techniques that are fast and reliable.

WLS technique has been widely used for solving the problem of state estimation. (1). Many variants of this WLS technique are available, each one thriving in its own way to generate a convincing estimate within a reasonable time. Though computationally simple, WLS based techniques are prone to the ill effects caused by the presence of bad measurements in the measurement vector and the focus has shifted towards obtaining a good estimate even in the presence of such bad measurements.

A SE algorithm, based on weighted least absolute value (WLAV) minimisation technique, has been alternatively used to handle power system problems [2-3]. Unlike WLS method, there is no explicit formula for the solution of WLAV algorithm but it can be reformulated as a linear programming (LP) problem. The estimate is then obtained by solving a sequence of LP problems. It is well known that this estimator is capable of automatically rejecting bad data, as long as the bad measurements are not leverage points, and hence found to be more robust than a WLS estimator [4].

The need for an efficient algorithm that occupies minimum memory and requires lower computation time has led to the development of fast decoupled state estimation (FDSE) [5-10] based on $P-\delta$ and $Q-V$ natural decoupling. The rate of convergence is strongly influenced by the initial voltages, which sometimes have a large δ and a poor V and the coupling between $P-\delta$ and $Q-V$ mathematical models. This coupling increases with system loading levels and branch r/x ratios, resulting in a decrease in the rate of convergence [11]. The decoupled method either failed to provide a solution or resulted in an oscillatory convergence on ill-conditioned power systems [12].

A fast decoupled WLAV state estimator with a constant Jacobian matrix realized through a few assumptions has been developed [13] and the technique, even faster, has generated an estimate which reflected the impact of assumptions made. Application of interior point method to solve the state estimation problem in WLAV formulation has been attempted [14].

Various formulations based on WLS and WLAV algorithms were used to obtain SE solutions [15-26]. There is a continuous interest in developing a reliable, robust and efficient algorithm, which occupies minimum memory, requires lower computation time and has the capability of rejecting bad measurements.

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A new SE algorithm in which line flows and voltage magnitudes as treated as state variables has been proposed in this work with a view to linearize the SE problem and to realize a constant jacobian matrix. This has been done through the manipulation of network equations and no assumptions have been made. The problem has been solved iteratively until convergence, for various loading conditions and the performance has been analysed on three standard test systems.

WLAV STATE ESTIMATION

The WLS estimator is not a robust one because of its quadratic objective function. Therefore, an estimator involving non-quadratic objective function is used. This estimator offers a more robust estimation, which is obtained by minimising

$$J = \left[diag(R^{-1})\right]^T \left|z - h(x)\right| \tag{1}$$

$$= \sum_{j=1}^{nz} \left|z_j - h_j(x)\right| / \sigma_j^{\,2} \tag{2}$$

Since the above objective minimises the absolute value of the error weighted by the measurement accuracy σ_j^{-2}, it is commonly called as the WLAV estimator.

The objective of Equation (1) is reformulated using LP in order to solve the WLAV problem:

Minimise $J = \left[diag(R^{-1})\right]^T \left[\gamma + \eta\right]$

Subject to (3)

$$H\,\Delta x + \gamma - \eta = \Delta z$$
$$\gamma, \eta \geq 0$$

A SE solution is obtained by solving the LP problem given by Equation (3) iteratively for x until Δx is sufficiently small. This method is highly inefficient, as it requires large computer memory and involves the time consuming LP technique, which itself is an iterative process and hence not suitable for real time applications. However this algorithm is robust and stable in the sense that it has the inherent feature of rejecting bad measurements by interpolating only ns among the nz measurements and free from ill-conditioning due to the effect of wide assignment of weighting factors and avoidance of factorisation and multiplication of several matrices. In this paper an attempt has been made to increase the computational efficiency of the robust WLAV technique through linearization.

PROPOSED METHOD

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

$$P_i = \sum_{j=1}^{nl} A_{ij}\ \ p_j - \sum_{j=1}^{nl} A'_{ij}\ l_j \tag{4}$$

$$Q_{i=} \sum_{j=1}^{nl} A_{ij}\ q_j - \sum_{j=1}^{nl} A_{ij}\ m_j \tag{5}$$

Treating P, Q and V_m^2 as state variable[x], the measurement set [Z] can be represented as

$$[Z] = [f(x)] \tag{6}$$

Where

$$[Z] = [P, Q, p, q, V^2]^T$$

The WLAV objective function can be written as

$$Min\ \varphi = \sum_{i=1}^{nm} wi\ [Zi - fi(x)] \tag{7}$$

The above equation does not include line capacitances and shunt susceptances and hence it is inadequate to estimate the system state. However the problem can be made solvable if constraint equations including branch voltage drop and phase angle drop are considered. These constraints can be represented as

$$h(x) =\ 2Rp + 2Xq - (\Lambda A_{1+}^T +\ A_{1-}^T)V^2 = 0 \tag{8}$$

$$g(x) = CXp - CRq - C\alpha = 0 \tag{9}$$

The constrained optimization problem of equations 7, 8 and 9 can be formulated as a linear programming problem as

$$Min\ \varphi = \sum_{i=1}^{nm} wi\ [Si' - Si'']$$

Subject to

$$A.\varDelta x + S' - S'' = Z - f(x^0)$$

$$H.\varDelta x = -h(x^0)$$

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$G.\Delta x = -g(x^0)$

Where

A, H and G are the jacobian matrices formed by partially differentiating f(x), h(x) and g(x) with respect to x.

Δx is the state correction vector

S' and S'' are the slack variable vectors.

The above Lp problem can be solved iteratively for x till the algorithm converges. It is to be noted that the jacobian matrices A, H and G are constant matrices that require to be computed only at the beginning of the iterative process.

However RHS vectors f(x), g(x) h(x) must be recomputed during iterative process.

ALGORITHM OF THE PROPOSED METHOD

a) Read the line data and load data.
b) Run the base case load flow and form the measurement vector.
c) Form the bus incidence matrix A.
d) Build the matrices for real and reactive power balance.
e) Form the matrix for loop phase angles.
f) From the above matrices form the necessary H, C, R and X matrices.
g) Reformulate SE problem as an LP problem by adding slack variables and add constraints to satisfy KCL and KVL.
h) Solve the SE problem by applying LP technique.
i) Check for convergence.
j) If converged, the procedure is stopped, otherwise state vector is updated and steps 8 and 9 are repeated till convergence is attained.
k) Increase the system load keeping load power factor constant and repeat steps 2 to 10

SIMULATION RESULTS

Simulation studies were carried out on standard IEEE 14, 30 and 57 bus test systems to study the performance of the proposed technique. The real and reactive power flows at both the ends of the transmission lines, bus power injections and bus voltage magnitudes were considered as measurements and real and reactive line flows and the bus voltage magnitudes were treated as state variables. Sufficient redundancy in the measurement vector has been brought in by considering the above mentioned measurements on all the odd numbered buses. The measurement vector has been generated by adding a low variance noise to the power flow results obtained from standard Newton Raphson technique. The performance has been tested under various loading conditions, starting from base load up to a load factor of 1.5. The loads on the system were gradually increased in steps keeping the load power factor constant.

Flat start with a convergence accuracy of 0.0001 has been assumed and three performance indicators have been considered to validate the algorithm.

$$\Delta Vrms = \sqrt{\frac{1}{nb}\sum_{i}^{nb}(V_i^t - V_i)^2} \quad (10)$$

$$\Delta p_{rms} = \sqrt{\frac{1}{nl}\sum_{i}^{nl}(P_i^t - P_i)^2} \quad (11)$$

$$\Delta q_{rms} = \sqrt{\frac{1}{nl}\sum_{i}^{nl}(q_i^t - q_i)^2} \quad (12)$$

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Table-1. IEEE 14 Bus System.

Load factor	Method	NET in ms	ΔVrms	ΔPrms	ΔQrms
1.0	WLAV	202	0.0569	0.0182	0.0065
	LFWLAV	98	0.00419	0.0063	0.0041
	WLS	187	0.0572	0.0177	0.0062
	LFWLS	78	0.0042	0.0059	0.0037
1.1	WLAV	203	0.0532	0.0188	0.0071
	LFWLAV	99	0.00412	0.0078	0.0046
	WLS	187	0.0543	0.0187	0.0072
	LFWLS	78	0.0046	0.0073	0.0037
1.2	WLAV	203	0.0506	0.0213	0.0086
	LFWLAV	99	0.00408	0.0084	0.0046
	WLS	178	0.0512	0.0211	0.0082
	LFWLS	76	0.0045	0.0081	0.0039
1.3	WLAV	203	0.0469	0.0241	0.0099
	LFWLAV	99	0.00401	0.0089	0.0048
	WLS	179	0.0481	0.0235	0.0092
	LFWLS	78	0.0047	0.0089	0.0042
1.4	WLAV	202	0.0439	0.0267	0.0108
	LFWLAV	99	0.00391	0.0098	0.0049
	WLS	182	0.0447	0.0258	0.0105
	LFWLS	79	0.0030	0.0098	0.0044
1.5	WLAV	203	0.0399	0.0294	0.0123
	LFWLAV	99	0.0039	0.0105	0.0053
	WLS	182	0.0414	0.0283	0.0116
	LFWLS	78	0.0045	0.0106	0.0047

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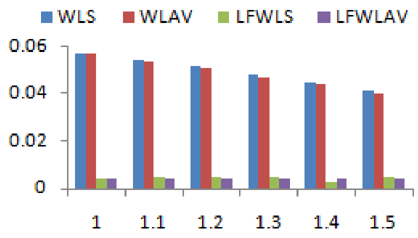

Fig. 1-Load Factor vs ΔVrms

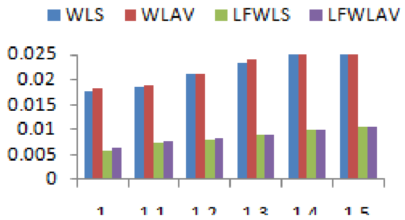

Fig. 2-Load Factor vs ΔPrms

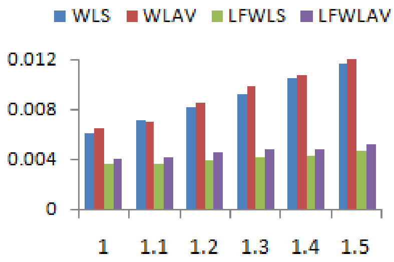

Fig. 3-Load Factor vs ΔQrms

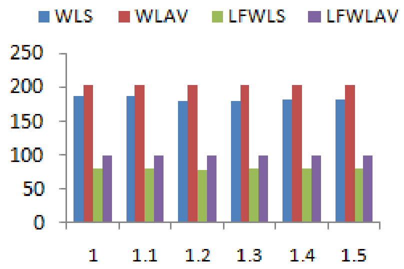

Fig. 4-Load Factor vs NET

Table-2. IEEE 30 Bus System.

Load factor	Method	NET in ms	ΔVrms	ΔPrms	ΔQrms
1.0	WLAV	593	0.0242	0.011	0.0103
	LFWLAV	133	0.00281	0.00436	0.0059
	WLS	561	0.0249	0.0107	0.0099
	LFWLS	97	0.0029	0.0043	0.0058
1.1	WLAV	595	0.0175	0.0115	0.0105
	LFWLAV	136	0.00265	0.00469	0.0065
	WLS	560	0.0179	0.0112	0.0106
	LFWLS	97	0.0027	0.0046	0.0062
1.2	WLAV	596	0.0167	0.0123	0.0119
	LFWLAV	136	0.00256	0.00498	0.007
	WLS	561	0.0171	0.0128	0.0114
	LFWLS	94	0.0029	0.0049	0.0066
1.3	WLAV	595	0.0154	0.0137	0.0125
	LFWLAV	134	0.00249	0.00498	0.0074
	WLS	561	0.0137	0.0137	0.0122
	LFWLS	97	0.0028	0.0049	0.0071
1.4	WLAV	596	0.0119	0.0148	0.0132
	LFWLAV	133	0.00241	0.00519	0.008
	WLS	562	0.0111	0.0148	0.0130
	LFWLS	97	0.0028	0.0052	0.0076
1.5	WLAV	596	0.0105	0.016	0.0139
	LFWLAV	135	0.00241	0.00528	0.0081
	WLS	561	0.0101	0.0158	0.0138
	LFWLS	97	0.0029	0.0059	0.0079

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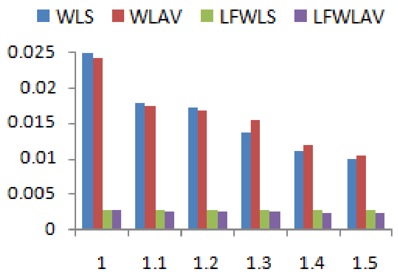

Fig. 5-Load Factor vs ΔVrms

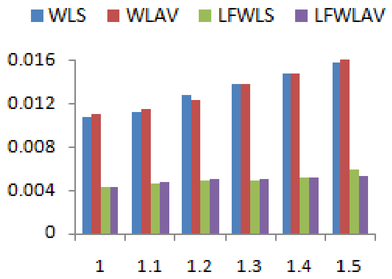

Fig. 6-Load Factor vs ΔPrms

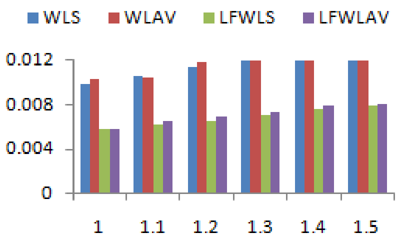

Fig.7-Load Factor vs ΔQrms

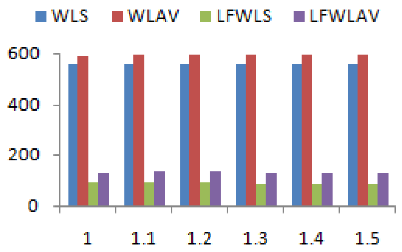

Fig. 8-Load Factor vs NET

Table-3. IEEE 57 Bus System.

Load factor	Method	NET in ms	ΔVrms	ΔPrms	ΔQrms
1.0	WLAV	1732	0.00929	0.0561	0.0989
	LFWLAV	184	0.0018	0.0191	0.0168
	WLS	1654	0.009223	0.0558	0.0986
	LFWLS	111	0.0018	0.0190	0.0167
1.1	WLAV	1789	0.00916	0.0569	0.0988
	LFWLAV	189	0.002	0.0186	0.0172
	WLS	1685	0.00920	0.0551	0.0986
	LFWLS	116	0.0022	0.0184	0.0178
1.2	WLAV	1811	0.00909	0.0573	0.0988
	LFWLAV	188	0.002	0.0194	0.0179
	WLS	1732	0.00925	0.0552	0.0986
	LFWLS	116	0.0020	0.0190	0.0185
1.3	WLAV	1820	0.00902	0.0576	0.0989
	LFWLAV	191	0.0019	0.0198	0.018
	WLS	1801	0.00929	0.0555	0.0987
	LFWLS	125	0.0020	0.0193	0.0179
1.4	WLAV	1821	0.00903	0.0579	0.0989
	LFWLAV	193	0.002	0.0199	0.018
	WLS	1798	0.00926	0.0554	0.0986
	LFWLS	125	0.0021	0.0199	0.0179
1.5	WLAV	1823	0.00903	0.0581	0.0988
	LFWLAV	194	0.002	0.0199	0.018
	WLS	1801	0.00920	0.0552	0.0986
	LFWLS	124	0.0021	0.0193	0.0178

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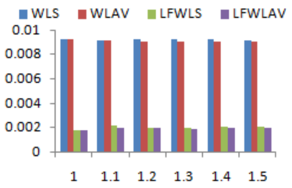

Fig. 9 - Load Factor vs ΔVrms

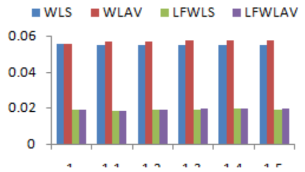

Fig. 10-Load Factor vs ΔPrms

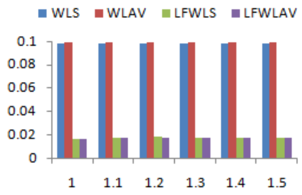

Fig.11-Load Factor vs ΔQrms

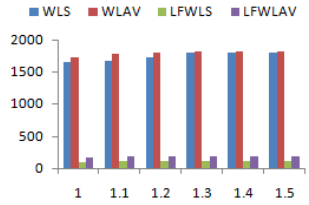

Fig. 12-Load Factor vs NET

Table-1 compares the performance of the proposed LFWLAV technique against WLS, LFWLS and WLAV techniques in terms of NET and solution accuracy.

It can be understood that the proposed method takes lesser execution time than that of the conventional WLS and WLAV techniques. The solution accuracy has remarkably improved due to the bad data rejection capability of WLAV and the partially decoupled problem formulation with constant jacobian significantly suppresses the computational burden imposed by the LP technique. Similar comparisons have been shown for IEEE 30 and 57 bus test systems in Table-2 and Table-3.

CONCLUSION

A novel line flow based WLAV state estimator has been developed for transmission systems and it has been tested on standard IEEE 14, 30 and 57 bus systems. Linearization and partial decoupling of the problem has been achieved without making any assumption and hence the proposed technique generates an estimate which closely agrees with the true system state. This technique consumes lesser execution time than that of the conventional WLS and WLAV techniques which make it one of the right choices for real time applications.

Nomenclature

LFBSE = Line Flow Based State Estimation
SE = State Estimation
WLS = Weighted Least Square
WLAV = Weighted Least Absolute Value
LP = Linear programming
FDSE = Fast Decoupled State Estimation
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
R^{-1} = Weight Matrix
σ_j = Variance of jth measurement
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 squares of the tap settings
A_{1+} and A_{1-} Positive and negative elements of A_1
S' and S'' = the slack variable vectors
λ and μ = Lagrangian multipliers
C = Loop incidence matrix
$\boldsymbol{\alpha}$ = Phase angle of the phase shifter, taken as 1 otherwise
ΔV_{rms}, Δp_{rms}, Δq_{rms} = Root Mean Square values of the corresponding deviations
V_i^{t}, p_i^t, q_i^t = True values of the respective quantities on i^{th} bus

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