A Revised Branch Current-Based Distribution System State Estimation Algorithm and Meter Placement Impact

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***Abstract*—With the development of automation in distribution systems, distribution supervisory control and data acquisition (SCADA) and many automated meter reading (AMR) systems have been installed on distribution systems. Also distribution management system (DMS) have advanced and include more sophisticated analysis tools. The combination of these developments is providing a platform for development of distribution system state estimation (DSE). A branch-current-based three-phase state estimation algorithm for distribution systems has been developed and tested. This method chooses the magnitude and phase angle of the branch current as the state variables. Because of the limited number of real-time measurements in the distribution system, the state estimator can not acquire enough real-time measurements for convergence, so pseudo-measurements are necessary for distribution system state estimator. The load estimated at every node from the AMR systems is used as a pseudo-measurement for the state estimator. The algorithm has been tested on three IEEE radial test feeders.**

In addition to this new strategy for DSE, another issue is meter-placement. This topic includes the type of measurement as well as the location of the measurement. Our results show the impact of these two issues on accuracy. Several general meter rules based on this analysis are outlined.

***Index Terms*—Automated meter reading, load estimation, meter placement, power distribution systems, state estimation.**

I. INTRODUCTION

WITH the reality of deregulation and competition, electric utilities need to provide cheap and reliable service to keep the customers happy. On the other hand, the technologies in the area of communications and computer engineering have advanced, and at the same time, the cost of the electronics has greatly reduced. So, many systems have been installed on the distribution systems, such as automated meter reading (AMR) systems and distribution supervisory control and data acquisition (D-SCADA) systems. These systems provide new data that can be used for distribution system analysis and control.

However, various constraints make it impossible to have a perfect picture of the system. First, because of the economical constraints, measurement instruments can not be installed every place where the measurements are needed, so the data are incomplete. Second, because of the nature of the measurement instruments and the communication problems in transmitting the data back to the control center, the measured data are subject to error or lost communication, so the data may be inaccurate, unreliable and delayed.

State estimation is one effective way to reduce these concerns. The state estimation technique is the process of producing the best possible estimates of the true value of the system states using whatever information is available. However, distribution systems have many features that are different from transmission systems. These include:

1) Radial topology;
2) Three-phase unbalanced system;
3) High resistance to reactance ratio and
4) Very limited number of real-time measurements.

All of these features make the distribution system state estimation more challenging. Transmission state estimation techniques cannot be applied directly to distribution systems.

The research on DSE started only about ten years ago, and much encouraging work has been done. Some DSE methods are proposed using node voltage magnitude and phase angle as the state variables [1]–[9].

In paper [1], Baran and Kelley developed a three-phase state estimation method, which is based on conventional weighted-least-squares and uses a three-phase node voltage formulation. It uses forecasted loads from historical load data as the pseudo-measurements. Authors Lu, Teng and Liu in paper [2] propose a three-phase distribution system state estimation algorithm. In the algorithm, the power measurements, current measurements and voltage measurements are converted to their equivalent currents, and the Jacobian terms are constant and equal to the admittance matrix elements. In paper [3], Lin and Teng proposed a current-based fast decoupled SE in rectangular-form. This work is the further development of the work in [2]. It decouples the constant gain matrix into two identical sub-gain matrices. Tests show that this revised algorithm has better performance in speed and memory usage than the full coupled one. In paper [4], they propose a fast decoupled three-phase state estimator with equality constraints. LaGrange multipliers are utilized to deal with the zero injections. The proposed method is based on the equivalent-current-measurement and rectangular coordinates.

K. Li in paper [5] proposed a DSE that not only gives a result of the system state, but also calculates the deviation of the bus voltages and power flow. The author also discussed the impact

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of measurement errors, correlation degree of load errors and measurement placement on the deviation of the estimated bus voltage.

In their paper [6], Ghosh, Lubkeman, Downey and Jones propose a probabilistic approach to distribution circuit state estimation, which uses a probabilistic extension of the radial load flow algorithm and accounts for real-time measurements as solution constraints. The output of the estimator also includes the confidence level for the estimated state. The field test results are discussed in paper [7]. It shows that the estimator is suitable for the feeders that have very little real-time measurements. The difficulties of implementing this method are also discussed in this paper.

The above methods are node voltage based DSE. Some DSE methods have been developed choosing the real and reactive part of the branch current as the state variables.

A branch-current-based three-phase state estimation method was proposed by Baran and Kelley in paper [8]. It is based on the WLS approach. The measurement function of the measurements on a given phase can be expressed as the function of current of that phase only, so the problem can be decoupled into three sub-problems. The method is tailored for weakly meshed distribution feeders with a few loops. The test case results show that this method has better performance compared to the conventional node-voltage-based methods both in computation speed and memory usage. In paper [9], Lin, Teng and Chen improved the algorithm proposed in [8]. The revised method decouples the real and imaginary parts of the current magnitude measurement and forms the constant gain matrix.

In this paper, a new branch current based distribution system state estimation algorithm is proposed. This algorithm uses the magnitude and phase angle of the branch current as the state variables.

Because of the limited real-time measurements in the distribution systems, the state estimator can not acquire enough real-time measurements, so pseudo-measurements are necessary for the distribution system state estimator. In recent years, an increasing number of Automated Meter Reading (AMR) systems have been installed. AMR can provide customer usage information and other data such as confirmations for outages and restoration. In this algorithm, the load estimated at every node from the AMR systems is used as the pseudo-measurements [10].

The next section outlines the revised branch current based distribution system state estimation algorithm.

II. State Estimation Algorithm

The algorithm uses the Weighted Least Square (WLS) method. The introduction of WLS based state estimation can be found in [11].

Table I lists the symbols used in this chapter.

TABLE I
Symbols Used in This Paper

Variables	Description
x	system state variable
k, m, s, t	system buses
p, q	different phases
P_k^p	injected real power at phase p of the bus k
Q_k^p	injected reactive power at phase p of the bus k
P_{km}^p	branch real power at phase p from bus k to bus m
Q_{km}^p	branch reactive power at phase p from bus k to bus m
$\tilde{V}_k^p$	complex voltage at phase p of the bus k, $\tilde{V}_k^p = V_k^p \angle \delta_k^p$
$\tilde{I}_{km}^p$	complex branch current at phase p from bus k to bus m, $\tilde{I}_{km}^p = I_{km}^p \angle \alpha_{km}^p$
$\tilde{Z}_{km}^{pq}$	impedance between phase p and q of branch from bus k to m, $\tilde{Z}_{km}^{pq} = Z_{km}^{pq} \angle \theta_{km}^{pq}$
$(\tilde{V}_k^p)^*$	conjugate of complex voltage $\tilde{V}_k^p$, $(\tilde{V}_k^p)^* = V_k^p \angle -\delta_k^p$
$(\tilde{I}_{km}^p)^*$	conjugate of complex branch current at phase p from bus k to bus m, $(\tilde{I}_{km}^p)^* = I_{km}^p \angle -\alpha_{km}^p$

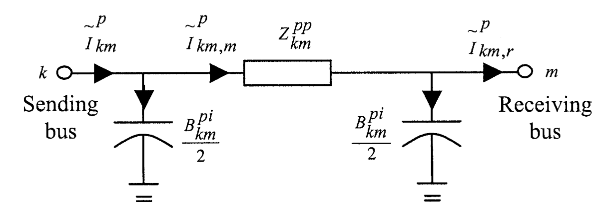

Fig. 1. Equivalent circuit of one phase of a branch line.

A. State Variables

The state variables used in this algorithm are the magnitude and the phase angle of the current in the branches. When a line is a little longer, the effect of the shunt capacitance causes a changing line current. Normally, the line can be represented by a π equivalent circuit. The shunt capacitance of the line is divided into two equal parts, each placed at the sending and receiving ends of the line. Fig. 1 shows the phase p of branch line from bus k to bus m. In this equivalent circuit, three different currents exist. In this state estimation algorithm the currents at the sending end $\tilde{I}_{km}^p$ is chosen as the state variables.

B. Entries of Jacobian Matrix

In this algorithm, the measurements that are widely used on the distribution systems are incorporated. They are real and reactive branch power measurements, current magnitude measurements, power injection measurements and voltage magnitude measurements.

The entries of the Jacobian matrix are derived by taking the differential of the measurement equations with respect to the state variables. In the distribution system, the three-phase model must be used. The measurement equations and the Jacobian entries are derived below.

1) Branch Power Measurements: The power of phase p from bus k to bus m at the bus k end can be stated as:

$$P_{km}^p + jQ_{km}^p = \tilde{V}_k^p \left(\tilde{I}_{km}^p\right)^* = V_k^p I_{km}^p \left[\cos\left(\delta_k^p - \alpha_{km}^p\right) + j\sin\left(\delta_k^p - \alpha_{km}^p\right)\right] \quad (1)$$

So the corresponding Jacobian matrix entries are:

1) When $km = st$ & $p = q$, that is, when the measurements and the state variables are in the same line segment:

$$\frac{\partial P_{km}^p}{\partial I_{st}^q} = V_k^p \cos\left(\delta_k^p - \alpha_{km}^p\right) = \frac{P_{km}^p}{I_{km}^p} \quad (2)$$

$$\frac{\partial P_{km}^p}{\partial \alpha_{st}^q} = V_k^p I_{km}^p \sin\left(\delta_k^p - \alpha_{km}^p\right) = Q_{km}^p \quad (3)$$

$$\frac{\partial Q_{km}^p}{\partial I_{st}^q} = V_k^p \sin\left(\delta_k^p - \alpha_{km}^p\right) = \frac{Q_{km}^p}{I_{km}^p} \quad (4)$$

$$\frac{\partial Q_{km}^p}{\partial \alpha_{st}^q} = -V_k^p I_{km}^p \cos\left(\delta_k^p - \alpha_{km}^p\right) = -P_{km}^p \quad (5)$$

2) Otherwise, when the measurements and the state variables are not in the same line segment, all the entries related to branch power measurements are zero.

2) Current Magnitude Measurements: The current of phase p from bus k to bus m can be stated as:

$$I_{km}^p(measurements) = I_{km}^p \quad (6)$$

So the corresponding Jacobian matrix entries are:

$$\frac{\partial I_{km}^p}{\partial I_{st}^q} = \begin{cases} 1 & (when\ km = st\ \&\ p = q) \\ 0 & (otherwise) \end{cases} \quad (7)$$

$$\frac{\partial I_{km}^p}{\partial \alpha_{km}^p} = 0 \quad (8)$$

3) Power Injection Measurements: Suppose the power injection is at bus k, and there are n buses $(1 \cdots n)$ connected to bus k, and the current flows from buses $1 \cdots m$ to bus k, and flows from bus k to buses $m+1 \cdots n$ (as shown in Fig. 2). That is, buses $1 \cdots m$ are bus k's upstream buses, and buses $m+1 \cdots n$ are bus k's downstream buses.

According to Fig. 1 and Fig. 2, the injection power of phase p at bus k can be stated as:

$$P_k^p + jQ_k^p = \tilde{V}_k^p \left(\sum_{i=1}^{m} \tilde{I}_{ik,r}^p - \sum_{i=m+1}^{n} \tilde{I}_{ki}^p\right)^* \quad (9)$$

So the corresponding Jacobian matrix entries are divided into three categories:

1) When the line segment is connected to the bus at which power is injected and related state variables are upstream of the measurement, there are two conditions:

i) The measurements and the state variables are in the same phase:

$$\frac{\partial P_k^p}{\partial I_{ik}^q} = V_k^p \cos\left(\delta_k^p - \alpha_{ik}^p\right) \quad (10)$$

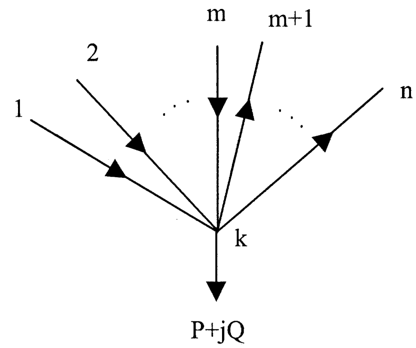

Fig. 2. One-line diagram of part of system for illustrating power injection measurements.

$$\frac{\partial P_k^p}{\partial \alpha_{ik}^q} = V_k^p I_{ik}^p \sin\left(\delta_k^p - \alpha_{ik}^p\right) \quad (11)$$

$$\frac{\partial Q_k^p}{\partial I_{ik}^q} = V_k^p \sin\left(\delta_k^p - \alpha_{ik}^p\right) \quad (12)$$

$$\frac{\partial Q_k^p}{\partial \alpha_{ik}^q} = -V_k^p I_{ik}^p \cos\left(\delta_k^p - \alpha_{ik}^p\right) \quad (13)$$

ii) The measurements and the state variables are not in the same phase, then the related entries are all zero.

2) When the line segment is connected to bus at which power is injected and the related state variables are downstream of the measurement, there are two conditions too:

i) The measurements and the state variables are in the same phase:

$$\frac{\partial P_k^p}{\partial I_{ik}^q} = -V_k^p \cos\left(\delta_k^p - \alpha_{ik}^p\right) \quad (14)$$

$$\frac{\partial P_k^p}{\partial \alpha_{ik}^q} = -V_k^p I_{ik}^p \sin\left(\delta_k^p - \alpha_{ik}^p\right) \quad (15)$$

$$\frac{\partial Q_k^p}{\partial I_{ik}^q} = -V_k^p \sin\left(\delta_k^p - \alpha_{ik}^p\right) \quad (16)$$

$$\frac{\partial Q_k^p}{\partial \alpha_{ik}^q} = V_k^p I_{ik}^p \cos\left(\delta_k^p - \alpha_{ik}^p\right) \quad (17)$$

ii) The measurements and the state variables are not in the same phase, then the related entries are all zero.

3) When the line is not connected to bus at which power is injected, then the related entries are zero.

4) Voltage Magnitude Measurements: Suppose the voltage magnitude is measured at bus k, and there are n branches $(1 \cdots n)$ connecting bus k $(n+1)$ to root bus 0, and all the branch currents are flowing away from the root bus (Fig. 3).

Using notation of Fig. 1 and 4, we can get:

$$\tilde{V}_{n+1}^p = \tilde{V}_0^p - \sum_{i=1}^{n+1} \sum_{q=A}^{C} \tilde{I}_{(i-1,i),m}^q \tilde{Z}_{i-1,i}^{pq} \quad (18)$$

The corresponding Jacobian matrix entries are divided into three categories:

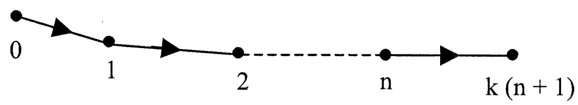

Fig. 3. One-line diagram of part of system for illustrating voltage magnitude measurements.

1) When the line segment is on the way from the bus at which voltage magnitude is measured to the source bus (line segment shown in Fig. 3):

$$\frac{\partial V_{n+1}^{p}}{\partial I_{i-1,i}^{q}} = -\cos\delta_{n+1}^{p}\cdot Z_{i-1,i}^{pq}\cos\left(\alpha_{i-1,i}^{q}+\theta_{i-1,i}^{pq}\right) - \sin\delta_{n+1}^{p}\cdot Z_{i-1,i}^{pq}\sin\left(\alpha_{i-1,i}^{q}+\theta_{i-1,i}^{pq}\right) \quad (19)$$

$$\frac{\partial V_{n+1}^{p}}{\partial \alpha_{i-1,i}^{q}} = \cos\delta_{n+1}^{p}\cdot I_{i-1,i}^{q}Z_{i-1,i}^{pq}\sin\left(\alpha_{i-1,i}^{q}+\theta_{i-1,i}^{pq}\right) - \sin\delta_{n+1}^{p}\cdot I_{i-1,i}^{q}Z_{i-1,i}^{pq}\cos\left(\alpha_{i-1,i}^{q}+\theta_{i-1,i}^{pq}\right) \quad (20)$$

2) When the line segment is not on the way from the bus at which voltage magnitude is measured to the source bus (line segment not shown in Fig. 3), the related entries are all zero.

It can be observed that most entries between measurements and state variables of different phases are 0, except the voltage magnitude measurement. After reviewing the (19) and (20), these entries can be approximated to 0 because the impedance between the different phases is very small, much smaller than that of the same phase. That is:

$$\frac{\partial V_{n+1}^{p}}{\partial I_{i-1,i}^{q}} \approx 0 \quad (when\; p \neq q) \quad (21)$$

$$\frac{\partial V_{n+1}^{p}}{\partial \alpha_{i-1,i}^{q}} \approx 0 \quad (when\; p \neq q) \quad (22)$$

After this modification the three phases are decoupled.

C. Algorithm Steps

The algorithm is implemented as the following steps:

1) Initialization

Initialization of the current magnitude and phase angle has a great impact on the convergence speed of the algorithm. In this implementation, a two step approach is used: a) Use a backward approach to get the initial value of current. In this step, set the initial value of voltage at every node to be a per unit value, and using the injected power at every node to calculate the branch current. b) Use a forward approach to get the initial value of voltage. In this step, using the branch current value calculated in a) and the root node voltage calculate the voltage at every node.

2) Calculate the updates of the system state (branch current) using (23) for the three phases separately.

$$\Delta x^{(n)} = \left[H^{T}\left(x^{(n)}\right)R^{-1}H\left(x^{(n)}\right)\right]^{-1} \times H^{T}\left(x^{(n)}\right)R^{-1}\left[z-h\left(x^{(n)}\right)\right] \quad (23)$$

where

z measurements.

$h()$ measurement function.

$H(x)$ the Jacobian matrix of the measurement function $h(x)$.

R the covariance matrix of measurement errors.

3) Update the branch current using (24) and using the forward approach to calculate the node voltage.

$$x^{(n+1)} = x^{(n)} + \Delta x^{(n)} \quad (24)$$

4) If $\Delta x^{(n)}$ is smaller than a convergence tolerance (stop criterion), then stop. Otherwise, if the number of iteration is smaller than the pre-set maximum iteration number, go to step 2), If it is not, it does not converge.

III. Test Cases and Meter Placement

A. Test Cases and Method Overview

The proposed three-phase distribution system state estimator was implemented using Microsoft Visual C++. The input data of the test system was stored in a Microsoft Access database.

Three feeders are tested. These three test cases are based on IEEE 13 Node, 34 Node and 123 Node Test Feeder radial distribution systems [12]. The three test cases are simplified to test the DSE algorithm. The common modifications to the three systems are:

1) The voltage regulators, transformers and switches are omitted, so the corresponding line segment and nodes are deleted.
2) The distributed load along the line segment is lumped and equally divided between the two end nodes of that line segment.
3) All the spot loads are changed into Y connected and constant PQ loads.

Radial Distribution Analysis Package (RDAP) [13] is used to do the power flow calculation of the test systems. The results of RDAP are treated as the true system states. The results of voltage magnitude, current magnitude and real and reactive branch power are used as the bases of the real-time measurements. The real and reactive load at every node given in the IEEE test feeders is used as bases of the pseudo-measurements. The simulated measurements are acquired by changing these measurements bases on a random percent of error. For all three test cases, the maximum error for the real-time measurements is 5% and 3% respectively, and for the pseudo-measurements (load) is 50% and 20% respectively. Testing also used the combinations of 50%-5% and 20%-3%. For all the test cases, the weight of pseudo-measurement was chosen as 0.01, and the weight of real measurements was 0.1.

And the results of the DSE are compared to the results of the RDAP to measure the performance of the DSE algorithm. In this paper, the average absolute error of node voltage magnitude and phase angle is chosen to measure the performance. Every test case is tested for 100 times and the average error is calculated.

In addition, for the economic reasons, there are only very limited number of real-time measurement devices that are installed on a distribution system. So it is important to determine what kind of measurement devices should be installed and where they

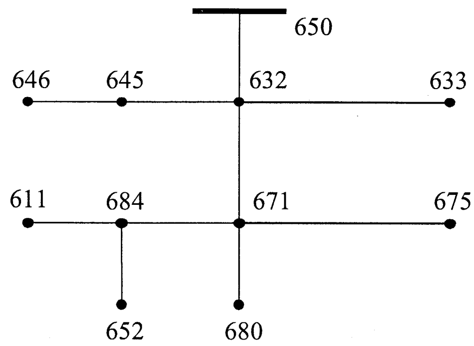

Fig. 4. One-line diagram of modified IEEE 13 node test feeder (modified from [12]).

TABLE II
MODIFIED IEEE 13 NODE TEST CASE VOLTAGE AVERAGE ABSOLUTE ERROR

Measurement	50%-5%		20%-3%	
	Mag.	Phase angle	Mag.	Phase angle
Pseudo Only	1.84%	0.90%	0.73%	0.36%
Pseudo & PQ (650-632)	0.41%	0.24%	0.20%	0.12%
Pseudo & PQ (671-675)	1.32%	0.65%	0.53%	0.26%
Pseudo & C (650-632)	0.83%	0.49%	0.35%	0.20%
Pseudo & C (671-675)	1.32%	0.72%	0.53%	0.28%
Pseudo & V (632)	2.56%	0.84%	1.51%	0.39%
Pseudo & V (675)	1.57%	0.70%	0.94%	0.31%

should be installed so that the distribution systems can be monitored to the best extent. In this paper, the impact of meter placement on the results of proposed state estimation algorithm is also studied.

The results of three test cases are given below.

B. Modified IEEE 13 Node Test Case

The one line diagram of the modified 13 node test system is shown in Fig. 4.

One real-time measurement in different places with all pseudo-measurements is tested. Table II shows the results. From the Table II, it can be seen that with one real-time branch power or current magnitude measurement installed, the results are better than those with only pseudo-measurements. It can also be seen that when these measurements are placed near the source and in the main feeder and near the source, the results are much better. On the contrary, if it is placed far from the source or in the lateral, the results are not much improved compared to the results with all pseudo-measurements. It can be concluded that the results of branch power measurement are best, and current magnitude measurement comes next. They are much better than the voltage magnitude measurement.

Table II also shows that with one real-time voltage magnitude measurement installed, the results are not always better than those with only pseudo-measurements. When the voltage magnitude measurement is placed near the source, the results are even worse. On the contrary, if it is placed far from the source, the results are slightly better than those with only pseudo-measurements. This is because the estimation results are more sensitive to the voltage magnitude measurements. Table III shows the results when improving the accuracy of the voltage magnitude measurement. From Table III, it is noted that with improved accuracy of voltage magnitude measurement, the results improve. This shows that the proposed state estimation algorithm requires higher quality for the voltage magnitude measurement.

TABLE III
VOLTAGE AVERAGE ABSOLUTE ERROR WITH ONE REAL-TIME VOLTAGE MAGNITUDE OF DIFFERENT MAXIMUM ERRORS

Measurement	50%-3%		50%-1%	
	Mag.	Phase angle	Mag.	Phase angle
Pseudo & V (632)	1.60%	0.75%	0.72%	0.70%
Pseudo & V (633)	1.56%	0.76%	0.75%	0.71%
Pseudo & V (671)	1.01%	0.67%	0.38%	0.64%
Pseudo & V (675)	0.95%	0.66%	0.39%	0.64%

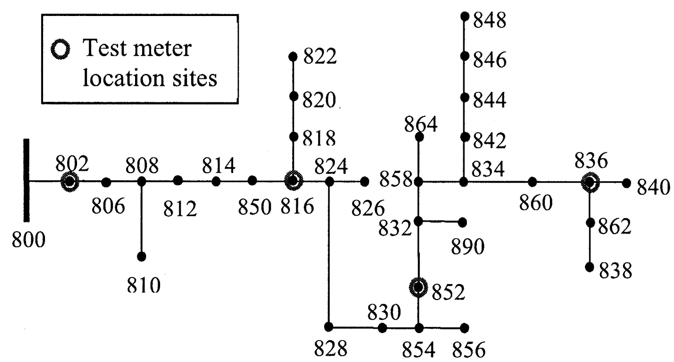

Fig. 5. One-line diagram of modified IEEE 34–node test feeder (modified from [12]).

C. Modified IEEE 34 Node Test Case

The one line diagram of the modified 34 node test system is shown in Fig. 5.

First, one real-time measurement in different places with all pseudo-measurements is tested. Four locations along the main feeder are chosen to place the meter (Fig. 5).

Fig. 6 and 7 show the voltage magnitude and phase angle error when one measurement installed in different locations (the maximum error is 50%-5%).

Next, the combination of the two real-time measurements is tested. The test results are shown in Table IV.

Table IV, it confirms that with more real-time measurements, the results are better, and placing real-time measurements in different locations can get better results than put them in the same location.

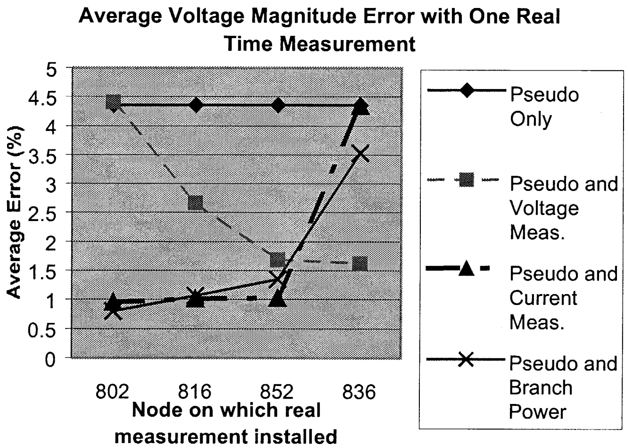

Fig. 6. Voltage magnitude error with one real-time measurement.

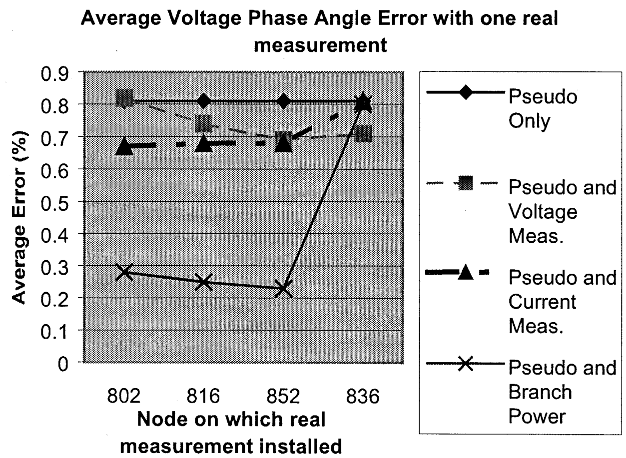

Fig. 7. Voltage phase angle error with one real-time measurement.

TABLE IV
VOLTAGE AVERAGE ABSOLUTE ERROR WITH TWO REAL-TIME MEASUREMENTS

Measurement	50%-5%		20%-3%	
	Mag.	Phase angle	Mag.	Phase angle
Pseudo Only	4.36%	0.81%	1.90%	0.33%
Pseudo & PQ (800-802) & PQ (816-824)	0.52%	0.17%	0.30%	0.10%
Pseudo & C (800-802) & C (816-824)	0.73%	0.68%	0.37%	0.27%
Pseudo & V (836) & V (852)	1.64%	0.70%	0.96%	0.28%
Pseudo & PQ (800-802) & C (800-802)	0.62%	0.27%	0.32%	0.14%
Pseudo & PQ (800-802) & C (816-824)	0.51%	0.26%	0.29%	0.14%
Pseudo & PQ (816-824) & C (800-802)	0.57%	0.22%	0.32%	0.12%
Pseudo & PQ (816-824) & C (816-824)	0.76%	0.23%	0.47%	0.13%
Pseudo & PQ (800-802) & V (836)	0.70%	0.28%	0.40%	0.15%
Pseudo & C (800-802) & V (836)	0.88%	0.73%	0.46%	0.31%

D. Modified IEEE 123-Node Test Case

The one line diagram of the modified IEEE 123-node test system is shown in Fig. 8.

First, one real-time measurement in different places with all pseudo-measurements is tested. Seven locations along the feeders are chosen to place the meter (Fig. 8). Table V shows part of the results.

The same trends of previous test cases can be found in Table V.

E. Summary of Meter Placement

From the above three test cases, some rules of meter placement for this proposed distribution system state estimation algorithm can be found:

1) The results of the branch power measurement are the best. The current magnitude measurement comes the second. They are much better than the voltage magnitude measurement.
2) Branch power and current magnitude measurements can get better results when they are installed near the source and in the main feeder which has many downstream nodes, while the voltage magnitude measurement can get better results when it is installed far from the source.

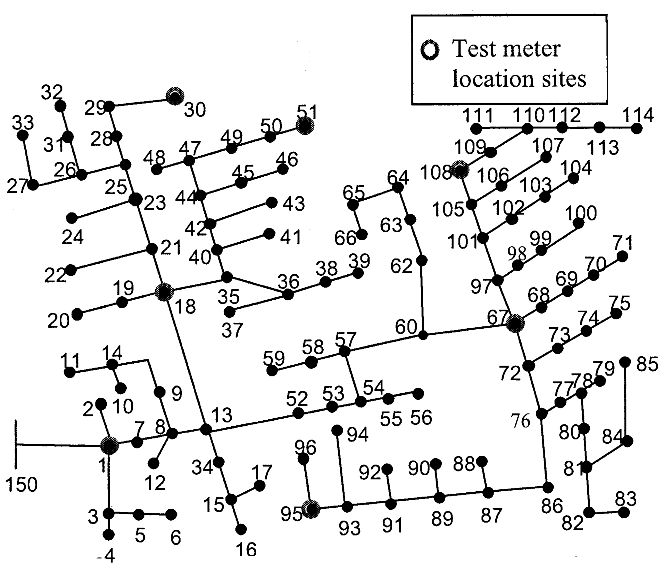

Fig. 8. One-line diagram of modified IEEE 123-node test feeder (modified from [12]).

3) When meters are placed at different locations, the results are better.

TABLE V
VOLTAGE AVERAGE ABSOLUTE ERROR WITH ONE REAL-TIME MEASUREMENT

Measurement	50%-5%		20%-3%	
	Mag.	Phase angle	Mag.	Phase angle
Pseudo Only	0.44%	0.23%	0.18%	0.09%
Pseudo & PQ (150-1)	0.28%	0.17%	0.15%	0.09%
Pseudo & PQ (13-18)	0.40%	0.21%	0.16%	0.09%
Pseudo & PQ (105-108)	0.43%	0.22%	0.17%	0.09%
Pseudo & C (60-67)	0.36%	0.18%	0.16%	0.07%
Pseudo & C (13-18)	0.41%	0.21%	0.17%	0.09%
Pseudo & C (93-95)	0.43%	0.23%	0.17%	0.09%
Pseudo & V (51)	0.44%	0.22%	0.19%	0.09%
Pseudo & V (30)	0.45%	0.22%	0.20%	0.09%
Pseudo & V (95)	0.41%	0.21%	0.20%	0.08%

IV. Conclusions and Future Work

In this paper, a revised branch-current-based three-phase distribution system state estimation algorithm was proposed, implemented and tested. The goal of this project was to get the snapshot of the state of the distribution systems as accurate as possible, using all the available information on the system. The proposed algorithm used data from an AMR system to estimate the loads on the distribution transformers, which are used as the pseudo-measurements for the distribution system state estimator. The branch-current DSE algorithm used current magnitude and phase angle as the state variable and decoupled the three phases to improve the computational speed. The algorithm incorporated all the major kinds of measurements of the distribution systems, including the voltage magnitude measurement. The impact of meter placement on the proposed estimator results was also studied.

The proposed distribution system state estimation algorithm provides satisfactory results and accomplished the desired outcomes. This work has provided a foundation related to DSE that can be extended in many areas. Future work can be broken down into three areas: more detailed models, more topologies, and testing on an actual system that has both AMR and other real measurements.

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References

[1] M. E. Baran and A. W. Kelley, "State estimation for real-time monitoring of distribution systems," *IEEE Trans. Power Syst.*, vol. 9, pp. 1601–1609, Aug. 1994.

[2] C. N. Lu, J. H. Teng, and W. H. E. Liu, "Distribution system state estimation," *IEEE Trans. Power Syst.*, vol. 10, pp. 229–240, Feb. 1995.

[3] W. M. Lin and J. H. Teng, "Distribution fast decoupled state estimation by measurement pairing," *Proc. Inst. Elect. Eng., Gen. Transm. Dist.*, vol. 143, no. 1, pp. 43–48, Jan. 1996.

[4] ——, "State estimation for distribution systems with zero-injection constraints," *IEEE Trans. Power Syst.*, vol. 11, pp. 518–524, Feb. 1996.

[5] K. Li, "State estimation for power distribution system and measurement impacts," *IEEE Trans. Power Syst.*, vol. 11, pp. 911–916, May 1996.

[6] A. K. Ghosh, D. L. Lubkeman, M. J. Downey, and R. H. Jones, "Distribution circuit state estimation using a probabilistic approach," *IEEE Trans. Power Syst.*, vol. 12, pp. 45–51, Feb. 1997.

[7] D. L. Lubkeman, J. Zhang, A. K. Ghosh, and R. H. Jones, "Field results for a distribution circuit state estimator implementation," *IEEE Trans. Power Delivery*, vol. 12, pp. 45–51, Feb. 1997.

[8] M. E. Baran and A. W. Kelley, "A branch-current-based state estimation method for distribution systems," *IEEE Trans. Power Syst.*, vol. 10, pp. 483–491, Feb. 1995.

[9] W. M. Lin, J. H. Teng, and S. J. Chen, "A highly efficient algorithm in treating current measurements for the branch-current-based distribution state estimation," *IEEE Trans. Power Delivery*, vol. 16, pp. 433–439, July 2001.

[10] H. Wang and N. N. Schulz, "A load modeling algorithm for distribution system state estimation," in *Proc. 2001 IEEE/Power Eng. Soc. Transm. Dist. Conf. Expo.*, pp. 102–106.

[11] A. J. Wood and B. F. Wollenberg, *Power Generation, Operaion and Control*, 2nd ed. New York: Wiley, 1996.

[12] W. H. Kersting, "Radial distribution test feeders," in *Proc. 2001 IEEE Power Eng. Soc. Winter Meeting*, pp. 908–912.

[13] Radial Distribution Analysis Package (RDAP)*http://www.zianet.com/whpower/whpc3.html* [Online]

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