PERFORMANCE EVALUATION OF STATE ESTIMATION FROM LINE FLOW MEASUREMENTS ON ONTARIO HYDRO POWER SYSTEM

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ABSTRACT

This paper reports the results of studies conducted to establish the feasibility of implementing the state estimation algorithm described by J.F. Dopazo et al (1,2) on the Ontario Hydro 230 KV and 500 KV networks. The results are consolidated into normalized graphs which can be used as a basis for design decisions related to implementation of state estimation on systems having topological characteristics similar to those of the network investigated. The paper describes a modification of the Dopazo algorithm which permits weighting of individual measurements rather than of transmission lines. The modified algorithm is shown to have excellent error detecting capabilities.

INTRODUCTION

Ontario Hydro is in the process of implementing an on-line Data Acquisition and Computer System (DACS). Besides a number of display and economy related software, DACS includes a comprehensive set of Security Application Programs (SAPS) to assist the Dispatchers with the security aspects of power system operations. The scope of the SAPS is to provide the facilities to enable:

1. Automatic checking of current operating conditions against operating limits with alarming of out of limits conditions.
2. Automatic checking of current system steady state performance for assumed predefined contingencies.
3. Simulation of control actions on the current operating conditions to check their correctness before effecting them.
4. Automatic and demand assessment of system security in a predictive mode with prediction time span up to three months.

At the time the SAPS were being formulated, it was recognized that their successful implementation depended very heavily on the on-line establishment of a data base which:

1. Is uncontaminated by statistical and systematic errors. This would eliminate the danger of false alarms from the automatic monitoring functions.
2. Describes the current operating conditions in terms of the system impedance model and Kirchoffs voltage and current laws. This is a fundamental requirement for the simulation type functions. It would also permit the dispatchers to relate the observed quantities in a logical manner without being distracted by inconsistencies with the electrical laws.
3. Permits computation of system quantities whose measurements are in gross error or which were not included in the metering scheme.

State estimation was recognized to be a necessary prerequisite to the establishment of such a data base. This paper describes studies carried out to establish the feasibility of on-line state estimation on the 230 KV and 500 KV Ontario Hydro system.

ALGORITHM SELECTION

The algorithm selected for the feasibility study was described by J.F. Dopazo et al (1,2) and is summarized in Appendix A. The main reasons for this selection were:

1. The algorithm requires complex line flow measurements. This data can be used directly for monitoring. This is of great practical importance since if the state estimation loses its significance due to excessive data loss, this does not result in complete loss of monitoring capability. Such capability can be increased significantly by the additional measurement of bus voltage magnitudes which can be done with little incremental cost.
2. The cost of gathering this data is equivalent to that of gathering data for other state estimation algorithms. While line flow measurements can be used with other algorithms, the data required for them is not necessarily usable with the selected algorithm.
3. The algorithm does not require measurements on all lines. In fact a solution can be obtained as long as measurements on any tree of the network are available. To illustrate this, if between two busses there is more than one line, the algorithm strictly requires measurements on one line only. Measurements on the other lines are redundant and thus contribute to error filtering. This feature diminishes the deleterious effects of data losses.
4. In essence, the algorithm solution relies on the inversion of a matrix closely related to the nodal admittance matrix of the portion of the network selected for state estimation. This realization was encouraging since it promised no new numerical difficulties associated with such inversion. This, of course, is of paramount importance on-line where such difficulties would be intolerable.

From here on, the Dopazo state estimation algorithm selected for investigation will be referred to as the "estimator".

SCOPE OF INVESTIGATION

The investigation was aimed at:

1. Evaluating the estimator performance in the face of errors in both the flow measurements and in the impedances of the network model.
2. Establishing the range of measurement errors over which the estimated solution compares favourably with the corresponding measured data. The estimator testing reported in the literature had been done assuming maximum CT and PT error bounds up to ±2%. This was considered an unrealistically low error to ensure which would have required a prohibitively expensive revamping of the system existing primary metering devices, and thus rule out the feasibility of state estimation.
3. Establish the importance of network topology to the performance of the estimator and ensure the topological adequacy of the Ontario Hydro network on which state estimation was being contemplated.
4. Evaluating the effect of errors in the magnitude of the reference voltage on the accuracy of the state estimation.
5. Evaluating the estimator gross error detecting capability.

METHOD OF ANALYSIS

The network and operating conditions selected for testing the estimator are shown in Figure 1. The network is part of the Ontario Hydro 230 kV and 115 kV system and was selected because it included both high impedance and very low impedance lines. This, combined with operating conditions with loaded as well as practically unloaded lines was considered of fundamental importance in assessing the estimator performance.

The line flows shown in Figure 1 were obtained with a load flow program and were taken to be the true solution to be estimated. The flow measurements were simulated by altering these flows using the expressions:

$$P_s = P_t + (A \times FS \times R_n + B \times FS \times R_{n+1} + C \times P_t \times R_{n+4}) / 100 \quad (1)$$

$$Q_s = Q_t + (A \times FS \times R_{n+2} + B \times FS \times R_{n+3} + C \times Q_t \times R_{n+4}) / 100 \quad (2)$$

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where:

P_s, Q_s = Simulated real and imaginary flow measurements respectively.

P_t, Q_t = True real and imaginary flows respectively.

FS = Full scale value for watt and var transducers and for A/D converters. In all the studies FS was assumed to be 500 MVA.

C = Error in potential and current transformers. This was expressed as a percentage of the MVA flow.

B = Error introduced by the watt and var transducers. This was expressed as a percentage of FS. In all the studies B was assumed to be 0.25%.

A = Error introduced by the A/D converters. This was expressed as a percentage of FS. In all the studies A was assumed to be 0.1%.

R_i = A random number with a value between ±1.0.

Under a given postulated accuracy of instrumentation, the maximum error which is apportioned by Equations (1) and (2) is obtained by setting the R_i's to unity:

$$\text{Maximum error in } Ps = \quad P_S = (A \times FS + B \times FS + C \times P_t)/100 \qquad (3)$$

$$\text{Maximum error in } Qs = \quad Q_S = (A \times FS + B \times FS + C \times Q_t)/100 \qquad (4)$$

This maximum error which can be present in any given simulated flow measurement will be referred to as the "error bound" for that measurement.

The impedances for the network model were simulated assuming that the impedances used for the load flow solution were exact. Errors were then introduced in accordance with the following equations:

$$Z_S = Z_t + (Z_{tr} \times E \times R_n)/100 + j\,(Z_{ti} \times E \times R_{n+1})/100 \qquad (5)$$

$$Y_S = Y_t + (Y_{tr} \times E \times R_{n+2})/100 + j\,(Y_{ti} \times E \times R_{n+3})/100 \qquad (6)$$

where,

Z_S = Simulated complex series line impedance

Z_t = True series complex line impedance from load flow.

Y_S = Simulated complex line charging.

Y_t = True complex line charging from load flow.

Y_{tr}, Z_{tr} = Real part of true line charging and true series line impedance.

Y_{ti}, Z_{ti} = Imaginary part of true line charging and true series line impedance.

E = Percentage impedance error.

R_i = A random number with a value between ±1.0.

TECHNIQUES USED TO EVALUATE ESTIMATOR PERFORMANCE

Since the distribution of errors in the power flows in the impedances of the network model were simulated using random numbers, different state estimation solutions would result from different patterns of error distributions. To evaluate the sensitivity of the goodness of the estimated solutions to different error distributions, for each postulated accuracy of instrumentation, 18 solutions were obtained each time using a different set of random numbers. The results were evaluated with respect to the true solution obtained from the load flow program.

The state estimation solutions obtained were evaluated by examining both the voltage solution and the power flows computed from it. The reason for this is that evaluating the results only from the voltage solution could be misleading because even though the individual voltages might appear sufficiently accurate the line power flows computed from these voltages might be unacceptable. To assess the results obtained from the 18 different sets of random numbers, the following procedure was adopted.

The goodness of the voltage solutions was evaluated by computing the standard deviations of the errors in the voltage magnitudes and phase angles.

The goodness of the estimated line flows was evaluated both qualitatively and quantitatively.

For the qualitative evaluation two types of graphs were plotted. To evaluate the magnitudes of the errors in the simulated flow measurements the following graphs were plotted for each set of 18 state estimation solutions:

a) Magnitude of errors in estimated MW flows.
b) Magnitude of errors in measured MW flows.
c) Magnitude of errors in estimated MX flows.
d) Magnitude of errors in measured MX flows.

Comparisons of the above four graphs provided at a glance a measure of the estimator performance.

To identify at a glance the estimator error amplification, four additional graphs were plotted. These were the same as the four graphs above with the difference that the error magnitudes were normalized on their respective error bounds. On these graphs, any points larger than one indicated error amplification.

Quantitatively the goodness of the estimated flows was evaluated by defining a Computed Data Quality Index (CDQI) as follows:

$$CDQI = \frac{Km}{Kc}$$

where,

Km = Standard deviation of the errors present in the simulated measured flows normalized on their respective bounds.

Kc = Standard deviation of the errors present in the computed flows normalized on their respective measured error bounds.

If CDQI > 1 then the overall accuracy of the computed data is better than that of the measured data. If CDQI = 1 then both measured and computed data are equivalent in overall accuracy. If CDQI < 1 then the overall accuracy of the measured data is better than that of the computed data.

ESTIMATOR PERFORMANCE WITH IMPEDANCE AND MEASUREMENT ERRORS

The goodness of the voltage solution under the postulated impedance and flow measurement errors can be assessed from Table I. Clearly the estimator generates voltage solutions which appear to be practically acceptable even under the most severe impedance and flow measurement errors simulated. It is of interest to notice that as the impedance errors increase, the estimated voltage magnitude actually improves slightly.

From Table I it can be concluded that the errors in the estimated voltages are acceptable in practice only if the voltages are used individually. The practical acceptability of these voltages when used in relation to one another can be assessed from Figure 2 which compares via the CDQI the overall accuracy in the measured data sets to the overall accuracy in the corresponding computed data sets. A study of Figure 2 discloses the following:

a) As expected, the CDQI curves obtained with impedance errors approach asymptotically the CDQI curves obtained with no impedance errors. For zero PT and CT errors the CDQI obtained taking into account impedance errors is practically zero. The only reason why it is not zero is the presence of A/D converter and watt and var transducer errors which introduce a bias in Figure 2.

b) In the case of a ±3.0% impedance error it is noted that:
   i) The overall accuracy of the computed MW flows is equal to or better than that of the measured ones when the PT and CT errors are in the range ±0.6% to ±12.0%.
   ii) The overall accuracy of the computed MW flows is equal

to or better than that of the measured ones when the PT and CT errors are larger than or equal to =1.60%.

The correctness of the observation in i) and ii) can be proven qualitatively. For example, Figures 6 and 7 were obtained with PT and CT errors of ±1.1%. Clearly these figures show that the computed data set is worse than the corresponding measured one as implied by ii) above. Figures 8 and 9 were obtained with PT and CT errors of ±4.15% and in accordance with ii) above show the computed data to compare favourably with measured data.

c) For the case of ±5.0% and ±10.0% impedance errors observations similar to those in (b) can be made. The incremental deterioration of the computed data set can be evaluated from Figure 2.

d) The range "R" of PT and CT absolute percentage error (C) within which the estimator is capable of producing a data set with overall accuracy better than that of the corresponding measured data set is:

for no impedance error: R = $0 < C < 12.20$

for ±3% " " : R = $1.60 < C < 12.00$

for ±5% " " : R = $3.7 < C < 12.00$

For impedance errors 7.5% and above, the estimator was never able to improve on the overall accuracy of the measured data set. Other ranges R for different postulated impedance errors can be obtained from Figure 3 which was obtained from Figure 2 and other studies not discussed.

The above results lead to the following conclusions:

1. The deterioration of the performance of the estimator due to impedance errors is significant. Keeping in mind that the usefulness of the state estimator is not limited to its ability to produce a data set of better overall accuracy, it is considered that from a practical viewpoint the impedance errors cease to be significant when the overall accuracy of the computed data set is equal to or better than that of the corresponding measured data set. Thus in practice an impedance error of ±5% is not significant for PT and CT errors above ±3.7%.
2. Figure 3 provides a basis for specifying metering accuracy for state estimation implementation. For example if the impedances are considered to be known within about ±5%, then from an engineering viewpoint it does not pay to require PT and CT combined errors smaller than about ±3.7%.

EFFECT OF ERRORS IN REFERENCE VOLTAGE

The effect of errors in the reference voltage was assessed by recomputing curves A and B in Figure 2 assuming various reference voltage errors. The results are summarized in Figure 4 which indicates:

1. The range "R" of absolute percentage PT and CT error over which the estimator is capable of improving the overall accuracy of the measured data reduces from: R = $1.6 < C < 12.0$ to:

 for ± 1% error: R = $1.6 < C < 11.8$.

 for ± 1.6% error: R = $2.0 < C < 10.8$

2. The estimated real power flows are not affected by the errors in the reference voltage.

From the studies conducted it was also noted that the estimated voltage level was shifted essentially by the same amount as the error present in the reference voltage.

From these results it is concluded that the largest tolerable error in the reference voltage is of the order of ±1.0%.

IMPORTANCE OF NETWORK TOPOLOGY

To assess quantitatively the importance of network topology studies were carried out to determine:

a) Deterioration in state estimation accuracy due to exclusion of parallel lines.

b) State estimation error filtering capability on a radial network.

c) The importance of metering both terminals of all lines. Note that from an estimating standpoint a line metered at both terminals is equivalent to two identical parallel lines each metered at one terminal only.

All studies were carried out assuming absence of gross errors. The salient results are summarized in Table II.

From Table II the following conclusions can be drawn:

1. Removal of parallel lines does not cause significant deterioration in the results. Thus the decision as to whether to include parallel lines in the metering scheme should be made on the basis of redundancy requirements to maintain the state estimator operating in the face of data loss and gross metering errors.
2. The estimate obtained on the radial network is much worse than obtained on the complete network. This is due to the fact that on a radial network the estimating problem degenerates into a unique solution. If measurements at both terminals of each line are taken then the solution is such that the voltage drop across each line is exactly the same as the average of the drops computed using the corresponding line terminal measurements. This averaging process results in filtering which is limited to the voltage drop across the individual lines. Clearly the inclusion of radial lines in the estimating network will slow down the computation without gaining any overall accuracy or error filtering capability.
3. Measurements at both terminals of every line are important. For example, with measurements at simple line terminals, in the case of impedance errors of ±5% the range of PT and CT errors within which the estimator improves the data quality reduces from $3.7<C<12.0$ to $6.5<C<12.0$ as can be seen from Figure 5. In addition, the metering of both terminals of every line increases considerably the estimator capability to survive data losses.

ESTIMATOR ERROR DETECTING CAPABILITY

The studies reported to this point evaluated the estimator performance when all measurement errors were within the bounds determined by the postulated accuracies of the metering equipment. In practice, however, some of the measurements will very likely be grossly in error from time to time. The practical usefulness of the estimator will depend, to a large extent, on its ability of discriminate bad data points and weight them out.

The line terminal whose flow measurements were to be given a gross error were selected at random using random numbers. The flow on the selected line terminals was modified according to

$$F_e = F_t + D + (G/100) \times F_t \tag{7}$$

where:

F_e = line terminal complex flow containing gross error

F_t = line terminal true complex flow

D = complex flow bias term

G = a variable to permit generation of different gross errors

The bias term D was introduced to avoid complete dependence of the magnitude of the gross error on the line flow. If this bias term is not used, then the magnitude of the gross errors on lightly loaded lines would be very small and therefore really not a gross error.

A number of error detection studies were made using the estimation algorithm of J.F. Dopazo et al (1,2). The results indicated that the algorithm error detection capability is not adequate. This is due to the fact that in formulating the estimator, it is assumed that for those lines for which flow measurements are available at both terminals, the voltage across them is computed as the average of the two voltages computed using the respective two line terminal flows.

This assumption worked well when the simulated measurements were contaminated with errors all within the postulated expected bounds. However, when the simulated measurements were in addition contaminated with gross errors, as would be the case in practice, the above assumption drastically weakened the estimator capability to discriminate the correctness of the terminal measurements in error. Any attempts at weighting out the suspected data points resulted in the weighting out of the entire lines which caused weakening of the estimating network connectivity thus further diminishing error filtering capability.

These problems were circumvented by modifying the algorithm to permit weighting of the individual data points as shown in Appendix A. The expression arrived at is:

$$\left[B_p^T(D_p + D_q)\, B_p\right] E = B_p^T \left[(D_p V_{mp} - D_q V_{mq}) - (D_p + D_q)\, A_g E_g\right] \qquad (8)$$

where the subscripted "p" and "q" denote quantities at the two terminals of each lines and the other variables are as described in Appendix A.

Equation (8) was used in the following error detection algorithm which is based on a "majority rule" principle. That is, given a data set, the solution tends to be biased towards the majority of the data items most likely within expected error bounds. For the remaining points which may be in gross error, the variance between measured and computed values would be largest indicating "nonconforming" and thus likely bad data points.

The algorithm procedure is:

1. Compute the error bound in MVA for each measurement. For the j^{th} measurement let this be EB_j.
2. Compute the voltage solution using the Dopazo algorithm with weighting factors set to unity.
3. Compute the difference in MVA between measured and computed flows. For the j^{th} measurement let this difference be DF_j.
4. Compute normalized variances for each measurement according to $Ri = \frac{DF_j}{EB_j}$, $j = 1, 2, \ldots n$. where n is the number of measurements.
5. If $R_j > 1.5$ then $W_j = \left[\frac{1}{R_j}\right]^2$, else $W_j = 1.0$.
6. Compute a new voltage solution with Equation (8) using the weighting factors computed in step 5 to compute the D_p's and D_q's.
7. Go back to step (3) four times.
8. All measurements for which $R > 2.0$ are grossly in error.

The above algorithm was found to work very well as shown by the results summarized in Table III. From this table, it is clear that for a network having topological characteristics similar to those of the network in Figure (1), the algorithm just described is capable of 100% error detection up to the point where about 12% of the total points are in gross error, and about 94% to 95% error detection when the points in gross error are in the range 14% to 24% of the total number of points. This, of course, assumes random instances of gross errors. In fact, if gross errors occur clustered in particular areas of the network, then error filtering and thus error detection is not possible. The false detection and the non-detection recorded in Table III were due to a cluster of 4 gross errors localized on lines 2, 3, 9, 20 in Figure 1.

CONCLUSIONS

1. The range of measurement and impedance errors over which the estimator was able to improve on the overall accuracy of the measured data set was found to be sufficiently wide to permit removing the fear that the actual errors which would in fact be encountered in practice might be too large to permit successful estimator implementation.
2. The topological characteristics of the Ontario Hydro network were proven to be sufficient for successful estimator implementation.
3. The accuracy requirement for the reference voltage was found to be within the capability of current technology.
4. The algorithm investigated in its original formulation was found to have inadequate error detecting capability. This problem was overcome by reformulating the algorithm to permit weighting of the individual measurements. In the modified formulation, the algorithm was found to have excellent error detecting capability.
5. On the basis of the results obtained, it was decided to implement the estimation algorithm investigated on the Ontario Hydro 230 kV and 500 kV networks.

The algorithm will be run in "error detection" and "estimating" modes. In the error detection mode, the error detection algorithm will be used and its function will be exclusively to maintain the measurements data set reasonably free from systematic gross errors. The rerun frequency for this mode of operation is a function of the frequency of new systematic error occurrences. It is estimated that if the error detection algorithm runs about once every two hours, this will be sufficient to keep the systematic gross errors to an acceptable level.

In the estimating mode the Dopazo algorithm will be used and its function will be to provide a consistent data base for monitoring and simulation application programs. The input to the algorithm will be the measurement set from which the systematic gross errors are continually being removed by the error detection algorithm.

APPENDIX A

Denote the terminals of each line as "p" and "q" terminal. The state estimation algorithm described by J.F. Dopazo et. al (2) iterates from a guessed voltage set to the estimated solution using the expression

$$(B^T D B)\, E = B^T D\, (Vm - AgEg) \qquad (1A)$$

where:

$\bar{E}$ = estimated vector of bus voltages

Vm = Vector of voltages across lines calculated from measured terminal flows and the E vector from previous iteration.

B = Bus/line incidence matrix with columns referring to reference busses removed.

B^T = Transpose of B

Ag = part of bus/line incidence matrix which refers to reference busses only

D = real diagonal matrix with $D_j = W_j \left|\frac{X}{Z_j}\right|^2$

where: W_j = weighting factor for measurement on line j

X = voltage at "p" terminal or voltage at "q" terminal both assumed one per unit

Z_j = impedance of line j

If each line is metered at both terminals, Equation 1A can be split into two equations:

$$(B_p^T D_p B_p)\, E_1 = (B_p^T D_p)\, (Vm_p - AgEg) \qquad (2A)$$

$$(B_q^T D_q B_q)\, E_2 = (B_q^T D_q)\, (Vm_q - AgEg) \qquad (3A)$$

where the subscripted "p" and "q" denote computation utilizing "p" and "q" terminal quantities respectively. By setting

$E_1=E_2=E$ to force a single solution and recognizing that $B_q=-B_p$, Equations (2A) and (3A) combine into the expression:

$$\left[B_p^T (D_p + D_q) B_p\right] E = B_p^T \left[(D_p Vm_p - D_q Vm_q) - (D_p + D_q)AgEg\right] \qquad (4A)$$

which permits weighting of the individual line flow measurements.

REFERENCES

1. J.F. Dopazo, O.A. Klitin, G.W. Stagg and L.S. VanSlyck, "State Calculation of power systems from line flow measurements" IEEE Trans (Power Apparatus & Systems) Vol. 89 pp. 1698-1708 September/October 1970.

2. J.F. Dopazo, O.A. Klitin and L.S. VanSlyck, "State Calculation of power systems from line flow measurements Part II", IEEE Trans (Power Apparatus & Systems) Vol. 91 pp. 145-151 January/February 1972.

3. R.E. Larson, W.R. Tinney, and J. Peschon, "State estimation in power systems, Part I: theory and feasibility", IEEE Trans (Power Apparatus and Systems) Vol. 89 pp. 345-352 March 1970.

4. R.E. Larson, W.R. Tinney and J. Peschon, "State estimation in power systems Part II: implementation and application", IEEE Trans (Power Apparatus and Systems) Vol. 89 pp. 353-359 March 1970.

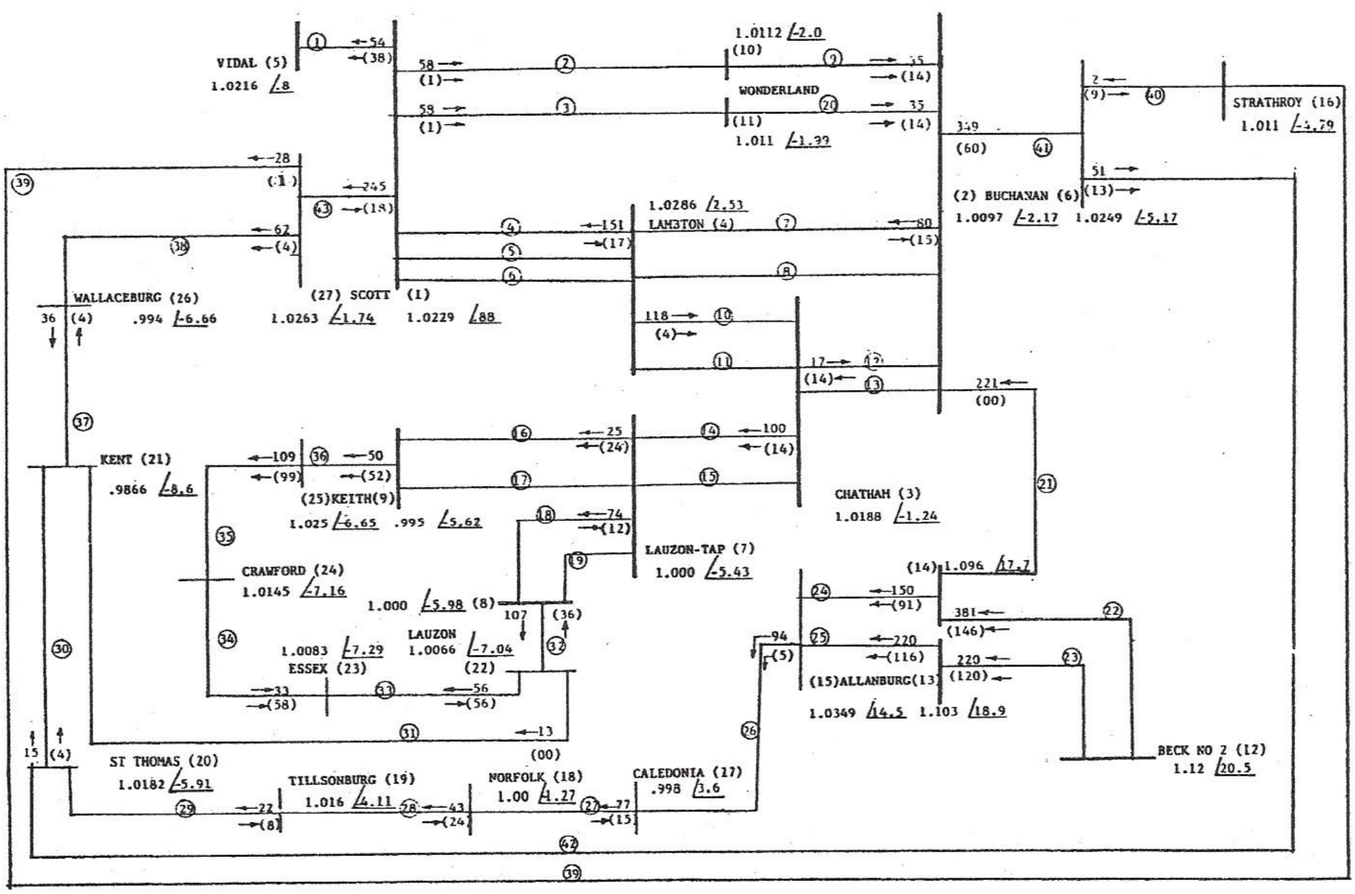

FIG. 1 NETWORK USED IN THE STUDY OF STATE ESTIMATION ALGORITHM. LINE NUMBERS ARE SHOWN WITHIN CIRCLES. BUS NUMBERS ARE SHOWN WITHIN PARENTHESES. FLOWS ON LINES ARE INDICATED BY ARROWS WITH REACTIVE FLOWS SHOWN IN PARENTHESES. FLOW VALUES HAVE BEEN ROUNDED OFF TO INTEGERS.

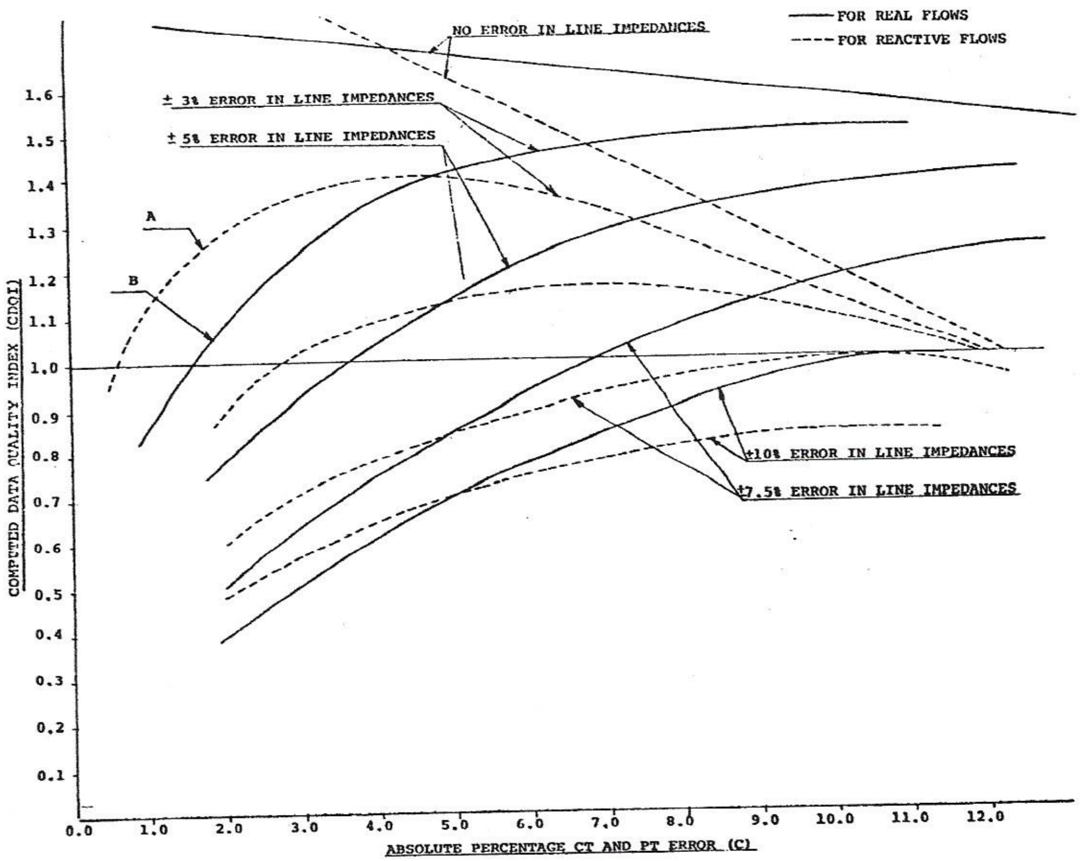

FIG.2. COMPUTED DATA QUALITY INDEX(CDQI) VS ABSOLUTE PERCENTAGE PT AND CT ERRORS(C).TRANSDUCERS AND A/D CONVERTERS ERRORS WERE KEPT CONSTANT AT ± 0.25 AND ± 0.1 PERCENT RESPECTIVELY,OF AN ASSUMED FULL SCALE OF 500 MVA.

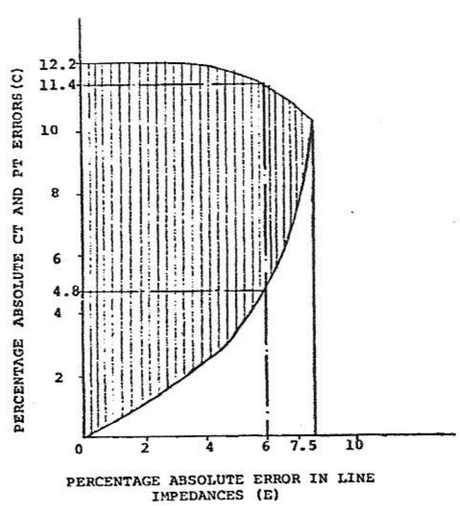

FIG 3 LET R BE THE RANGE OF ABSOLUTE PERCENTAGE PT AND CT ERRORS (C) WITHIN WHICH THE ESTIMATOR PRODUCED A DATA SET SUPERIOR IN OVERALL ACCURACY THAN THAT OF ITS CORRESPONDING MEASURED DATA SET. THE SHADED AREA DEFINES R AS FUNCTION OF MODELLING IMPEDANCE ERRORS. FOR EXAMPLE IF THE IMPEDANCE ERROR IS ESTIMATED TO BE ± 6%, THEN R = 4.8<C<11.4.

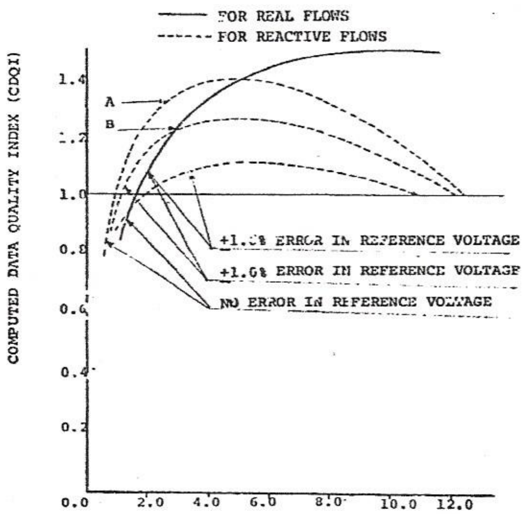

FIG 4 EFFECT OF ERROR IN THE MAGNITUDE OF REFERENCE VOLTAGE ON COMPUTED DATA QUALITY INDEX (CDQI). ERROR IN LINE IMPEDANCES WAS ASSUMED TO BE ± 3.0 PERCENT. ERROR IN REFERENCE VOLTAGE DID NOT AFFECT ACCURACY OF THE ESTIMATED REAL FLOWS.

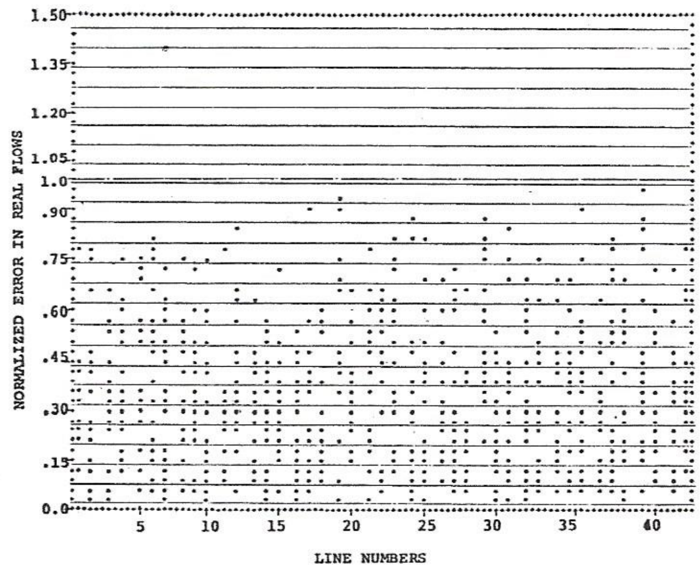

FIG 6 SPREAD OF NORMALIZED ERROR IN THE REAL FLOW MEASUREMENTS ON EACH LINE OBTAINED WITH 18 DIFFERENT SETS OF RANDOM NUMBERS. MEASUREMENTS WERE SIMULATED WITH EQUATIONS 1, 2 WITH A, B, C AND FS VALUES SET AT 0.1, 0.25, 1.1 and 500.0 RESPECTIVELY. THE LINE NUMBERS CORRESPOND TO THOSE INDICATED IN FIG. 1.

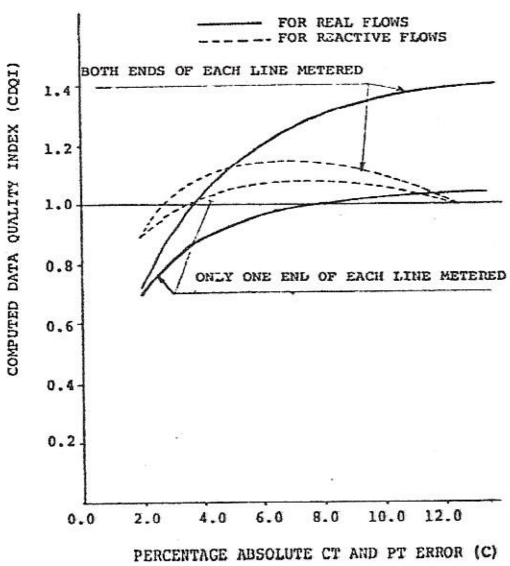

FIG 5 EFFECT OF METERING BOTH ENDS OF EVERY LINE ON COMPUTED DATA QUALITY INDEX (CDQI). ERROR IN LINE IMPEDANCES WAS ASSUMED TO BE ± 5.0 PERCENT.

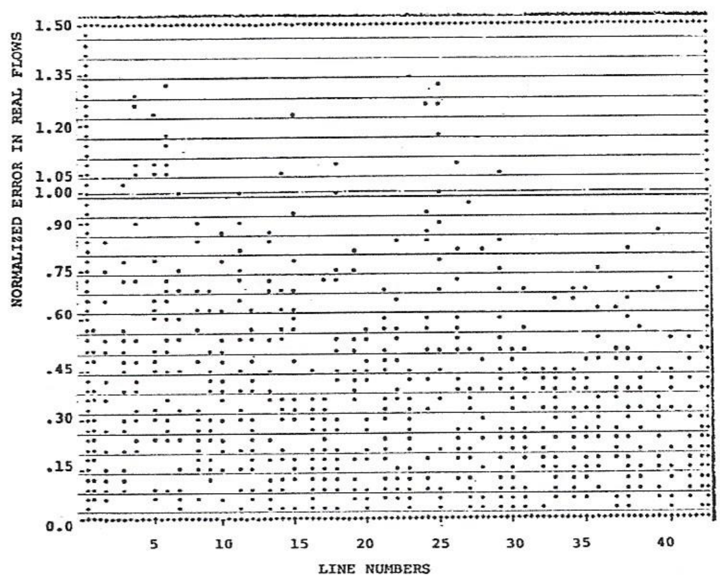

FIG 7 SPREAD OF NORMALIZED ERROR IN COMPUTED REAL FLOWS FOR 18 STATE ESTIMATION SOLUTIONS CORRESPONDING TO 18 DIFFERENT DISTRIBUTIONS OF MEASUREMENT ERRORS OBTAINED WITH 18 DIFFERENT SETS OF RANDOM NUMBERS. THE MEASUREMENT ERRORS, THE SPREAD OF WHICH IS SHOWN IN FIG 6, WERE SIMULATED WITH EQUATIONS 1, 2 WITH A, B, C AND FS VALUES SET AT 0.1, 0.25, 1.1 and 500.0 RESPECTIVELY. ERROR IN LINE IMPEDANCES WAS ASSUMED TO BE UP TO ± 3.0 PERCENT.

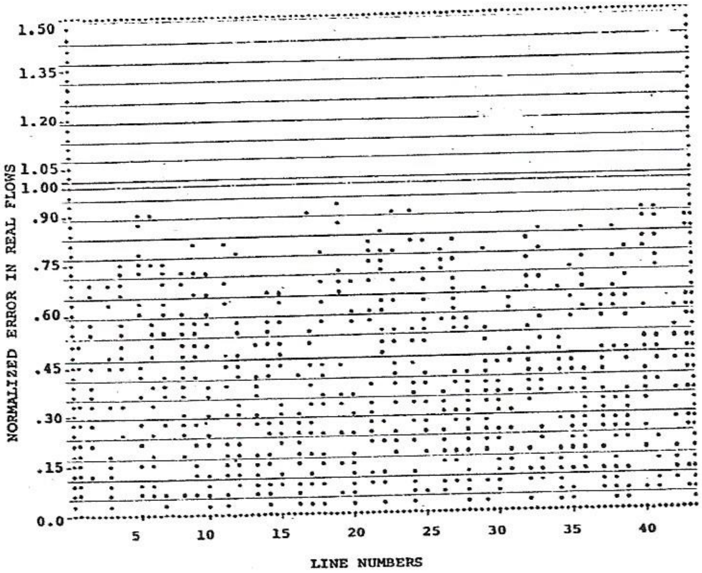

FIG 8 SPREAD OF NORMALIZED ERROR IN THE REAL FLOW MEASUREMENTS ON EACH LINE OBTAINED WITH 18 DIFFERENT SETS OF RANDOM NUMBERS. MEASUREMENTS WERE SIMULATED WITH EQUATIONS 1, 2 WITH A, B C AND FS VALUES SET AT 0.1, 0.25, 4.15 AND 500.0 RESPECTIVELY. THE LINE NUMBERS CORRESPOND TO THOSE INDICATED IN FIG. 1.

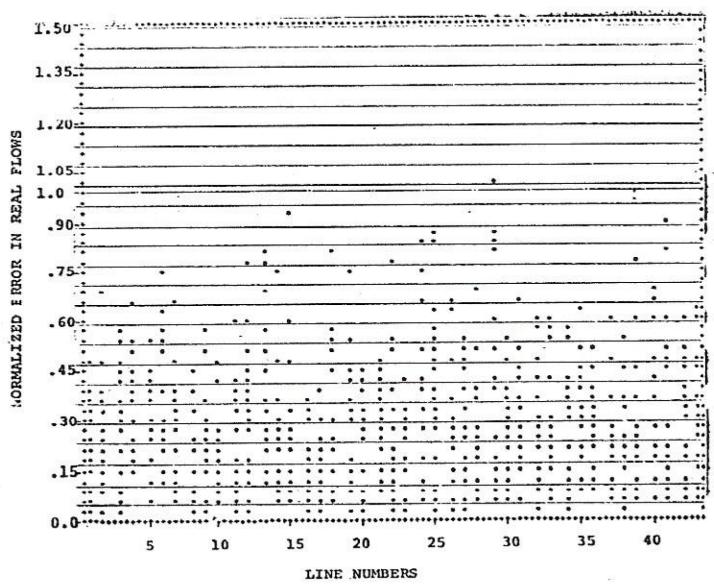

FIG 9 SPREAD OF NORMALIZED ERROR IN COMPUTED REAL FLOWS FOR 18 STATE ESTIMATION SOLUTIONS CORRESPONDING TO 18 DIFFERENT DISTRIBUTIONS OF MEASUREMENT ERRORS OBTAINED WITH 18 DIFFERENT SETS OF RANDOM NUMBERS. MEASUREMENT ERRORS, THE SPREAD OF WHICH IS SHOWN IN FIG 8, WERE SIMULATED WITH EQUATIONS 1, 2 WITH A, B, C AND FS VALUES SET AT 0.1, 0.25, 4.15 and 500.0 RESPECTIVELY. ERROR IN LINE IMPEDANCES WAS ASSUMED TO BE UP TO ± 3.0 PERCENT.

TABLE I

Errors in the Voltage Solution With and Without Errors in the Impedances. Errors Due to Transducers and to A/D Converters were Assumed to be 0.25 and 0.1 Per Cent of 500 MVA Full Scale Respectively.

	ERROR IN VOLTAGE MAGNITUDE (Per Unit)				ERROR IN VOLTAGE PHASE ANGLE (Degrees)				
Impedance Error (%)	Maximum Standard Deviation	Minimum Standard Deviation	Average Standard Deviation	Maximum Actual Error	Maximum Standard Deviation	Minimum Standard Deviation	Average Standard Deviation	Maximum Actual Error	Combined PT and CT Errors (C)
	0.0011	0.0002	0.0005	0.0011	0.1392	0.0012	0.05086	0.3	2.0
	0.0013	0.0002	0.0006	0.002	0.2251	0.0015	0.07798	0.4	3.5
± 0.0	0.0017	0.0002	0.0007	0.003	0.3121	0.0018	0.1065	0.6	5.0
	0.0023	0.0002	0.0008	0.005	0.4373	0.0024	0.1482	0.8	7.15
	0.0038	0.0002	0.0011	0.007	0.7293	0.004	0.2465	1.3	12.0
	0.0013	0.0002	0.0006	0.002	0.2599	0.0021	0.08811	0.6	1.1
	0.0013	0.0002	0.0006	0.002	0.2684	0.0020	0.09333	0.7	2.0
± 3.0	0.0012	0.0003	0.0006	0.002	0.2884	0.0020	0.1026	0.75	3.0
	0.0012	0.0002	0.0006	0.002	0.3225	0.0020	0.1168	0.8	4.15
	0.0015	0.0003	0.0007	0.0035	0.3944	0.0021	0.1445	0.9	6.0
	0.0017	0.0002	0.0007	0.004	0.4459	0.0023	0.1637	1.0	7.15
	0.0017	0.0002	0.0008	0.0035	0.4270	0.0029	0.1427	1.0	2.0
	0.0015	0.0003	0.0007	0.003	0.4394	0.0028	0.1519	1.1	3.5
± 5.0	0.0014	0.0003	0.0007	0.003	0.4696	0.00305	0.1661	1.2	5.0
	0.0016	0.0002	0.0008	0.0032	0.5342	0.0028	0.1932	1.3	7.15
	0.0022	0.0003	0.0009	0.005	0.6464	0.0032	0.2366	1.4	10.0
	0.0027	0.0002	0.0010	0.007	0.7601	0.0036	0.2789	1.6	12.5
	0.0036	0.0002	0.0013	0.0040	0.8566	0.0054	0.2758	1.9	2.0
± 10.0	0.0025	0.0003	0.0012	0.0044	0.8439	0.0051	0.2857	2.1	5.0
	0.0025	0.0003	0.0012	0.0046	0.9229	0.0048	0.3273	2.3	10.0

TABLE II

Results of Studies to Evaluate Importance of Network Topology. Results Shown were obtained Assuming PT and CT Errors of ±5.0%, the Transducers and A/D Converter Errors were Assumed at 0.25% and ±0.1%, Respectively, of a Full Scale of 500 MVA. Error in the Impedance of Lines was Assumed to be ±5%.

Circuit Configuration	Maximum Standard Deviation		CDQI Computed Using Estimated Flows on Complete Network	
	Voltage Magnitude (PU)	Voltage Angle (Degrees)	MW	MX
Complete Network (Figure 1)	.0014	.4696	1.12	1.13
Network Without Parallel Lines (lines 4, 5, 7, 10, 12, 14, 16, 18 in Figure 1 removed)	.0018	.5721	.97	.96
Complete Network with Measurement at One End of Each Line (for complete results see Figure 5)	.0024	0.478	.935	1.04
Radial Network (lines 3, 6, 12, 24, 31, 34, 39, 40, 42 in Figure 1 removed)	.0045	.899	.35	.40
Radial Network with Measurement at One End of Each Line	.005	.9875	.275	.316

TABLE III

Results of Studies to Evaluate Algorithm Gross Error Detecting Capability. The Gross Errors Were Simulated with Equation (7) with D Set at 10.0+j 10.0 MVA. The Value for G is Shown in the Table. For these studies PT and CT Errors Were ±5.0%, Impedance Errors ±5.0%, and Transducers and A/D Converters Errors ±0.25% and ±0.1% Respectively.

G		20.0								40.0							
Points in gross error	Number of points	6	9	12	15	18	20	25	29	6	9	12	15	18	20	25	29
	Percentage of total points	7	10	14	17	21	23	29	34	7	10	14	17	21	23	29	34
Correct detections	Number of points	6	9	11	14	17	19	24	25	6	9	11	14	17	19	24	24
	Percentage of total points in error	100	100	92	93	94	95	96	86	100	100	92	93	94	95	96	83
False detections	Number of points	0	0	1	1	1	1	1	7	0	0	1	1	1	1	1	9
	Percentage of total points not in error	0	0	8	7	6	5	4	24	0	0	8	7	6	5	4	31
Points in gross error not detected	Number of points	0	0	1	1	1	1	1	4	0	0	1	1	1	1	1	5
	Percentage of total points in gross error	0	0	8	7	6	5	4	14	0	0	8	7	6	5	4	17

Discussion

K. Srinivasan and **Y. Robichaud** (Hydro-Québec Institute of Research, Varennes, P.Q., Canada): The authors have made a significant contribution by testing systematically, a variation of the state estimation algorithm of Dopazo et al. Uncertainties in the power measurements, in impedance data and in voltage reference magnitude have been considered.

For absolute percentage PT and CT errors greater than about 5%, Figure 2 and Figure 4 show that the Computed Data Quality Index (CDQI) is better for real flows than reactive flows. Have the authors considered separately the effects of real and reactive power measurement inaccurracies.

Could the authors elaborate on the uniform distribution of errors used in the simulations and whether they have obtained similar test results with gaussian uncertainties also.

The modification of the Dopazo's algorithm proposed by the authors appears quite redundant. This is due to the fact that individual weighting of measurements can be made permissible in the original algorithm itself, by considering the lines with both ends measured as though they were two parallel identical lines with one measurement each. Could the authors comment on this?

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R. D. Masiello (Leeds & Northrup Company, North Wales, Pa. 19454): The results presented in this paper will undoubtedly be extremely valuable to engineers evaluating approaches to state estimation for their own systems in terms of requirements and benefits. Several interesting questions are raised.

First, the authors conclude that there is maximum tolerable error of 1% in reference voltage. This seems to be a severe requirement in light of their previous statements about feasible meter accuracies.

Second, from the observation that a radial line metering allocation provides relatively poor results the conclusion is made that radial lines will not improve accuracy by their inclusion in a more complete metering scheme. As stated in the text, the tests do not make this conclusion immediately obvious. Perhaps the authors could clarify this point.

Third, the error detecting mode of the algorithm could be an important feature of an implemented algorithm. It leads to a speculation that the weighting factor adjustment could be included inside the iterative process with a hopeful savings in computation time. Have the authors attempted such a scheme? Again, the authors are to be congratulated on a well planned evaluation of estimation capabilities and requirements, including many important effects not previously considered.

Manuscript received February 13, 1973.

J. F. Dopazo, O. A. Klitin, and **A. M. Sasson** (American Electric Power Service Corporation, New York, N.Y. 10004): The authors should be congratulated for this excellent paper. The analysis presented on the measurement accuracy requirements relative to the accuracy of the impedance values is an important contribution for the practical implementation of state estimation. We wish to thank the authors for their thorough evaluation of our algorithm. However we would like to clarify a misinterpretation which resulted in a conclusion that the algorithm detection capability is not adequate. The authors interpreted that the voltage across the network elements is computed as the average of the two voltages obtained from the respective flow measurements at the two line ends. This is true only for the case where the measurement at one end is lost while the other one is available. In this case, the available measurement is used for both ends and the resulting voltages across the elements are averaged. This artifice avoids the need for modification of the gain matrix. For the case where measurements are available at both ends, the voltages obtained from the various measurements are treated individually and no averaging is performed. This can be inferred from the fact that the sum of the errors squared function that we minimize spans the entire range of measurements. It is interesting to mention that the final equation the authors arrive at in Appendix A can be obtained from our formulation if the matrix operations are performed in partitioned form.(1)

We have found that the detection and identification of gross measurement errors by observing the residuals (measured minus computed flows) is not always reliable. The least squares algorithm can produce a closer fit at the bad data location than in some surrounding points, thus introducing a smearing effect. Will the authors comment on their observations on this question?

Our previous papers have not fully covered the problem of detecting and identifying gross measurement errors. Details on our technique for the solution of this problem will be presented on a forthcoming paper at the 1973 PICA Conference. (2)

[1] A. M. Sasson, discussion to Reference 2 of the paper.
[2] J. F. Dopazo, O. A. Klitin, A. M. Sasson, "State Estimation for power systems: detection and identification of gross measurement errors," submitted to the 1973 IEEE PICA Conference

Manuscript received February 16, 1973.

Berardino Porretta and **R. S. Dhillon:** We would like to thank all the discussers for their comments and for the interest shown in our work.

The following is in reply to the discussion by Messrs J. F. Dopazo, O. A. Klitin and A. M. Sasson.

Our interpretation of the measurement processing used in the algorithm of the discussers is based on equations in references (1) and (2) of paper and on the good results we have obtained with it. As an example in Mr. Sasson's discussion to reference (2) of the paper, equation 31 is derived assuming $Dp \approx Dq$. If we apply the assumption throughout this equation can be written as

$$(B^T DB)\, E = B^T D \,\frac{(Vmp - Vmq)}{2}$$

which clearly averages the two voltages computed from the terminal flows for each line.

We fully agree with the assumption $Dp \approx Dq$ since in practice there is no data, other than nominal instrument accuracy classification, on the basis of which the accuracy of the instrumentation used for the measurements at both terminals of the lines can be differentiated. The results of our studies have shown that the above assumption gives good results from the point of view of using the computed data for operating purposes even when 10% of the measured flows were in gross error.

However when the estimator is used for error detection this assumption produces unacceptable variances at a number of good data points as well as at the bad data points. This "smearing" makes discrimination of the good data points from bad data points impossible. The error detection algorithm presented in the paper is capable to "see through" the smearing, and picks out the points which are really in gross error in three to four iterations by attaching different weighting factors to line terminal measurements. As noted in the paper, we will be running the state estimator in "error detecting" and "estimating" modes. In the estimating mode we will be assuming $Dp = Dq$.

We do not understand the statement that in case the measurement at one line terminal is lost, the remaining measurement can be applied to both terminals of the line. In general the reactive flow on the two terminals of a line will be significantly different. On this basis we would use the line voltage computed from the line end with the remaining measurement twice, rather than computing two line voltages from the two line ends using one measurement.

The following is in reply to Mr. R. D. Masiello.

The reason why we stated that the maximum error in reference voltage should not exceed 1% is that this amount of error does not in our judgement appreciably affect the accuracy of results produced by the estimator. This is not considered a "severe requirement" if it is kept in mind that this accuracy is required for only one voltage measurement. The stated 1% accuracy is easily obtained with wound type potential transformers.

In the paper we tried to make the point that the error filtering capability of state estimation on a radial network is very limited. If all the lines in a radial network are measured on both ends, some error filtering will be possible due to averaging of line voltages derived from measurements made at both ends of the line. If, for example we had a radial network where each line is measured at one end only, the solution in this case is uniquely defined and no error filtering of any kind will be possible because the computed and the measured data will match exactly no matter how wrong the measured data is.

In the on line implementation of our state estimator we intend to adjust the weighting factors in the iterative process itself when the state estimator will work in the error detection mode.

The following is in reply to Messrs. K. Srinivasan and Y. Robichaud.

The effects of inaccuracies in real and reactive flows were not considered separately. Actually the errors in both real and reactive flows were simulated using equations 1,2 in the paper and the errors in computed real and reactive flows were compared with corresponding errors in measured real and reactive flows.

In our simulation studies we assumed that accuracies of all the instruments was always within specified limits and within those bounds instrumentation error was uniformly distributed. We did not try any other distribution because we could not convince ourselves that there was any basis for doing it. Large errors in instrumentation were simulated while checking the ability of algorithm to detect gross error.

Formulation given in the Appendix A of our paper can certainly be derived by representing each line with two measurements as two lines each with one measurement. This approach obtains the same final results but conceals some of the assumptions used in arriving at the final results such as E_1 obtained from equation 2A is equal to E_2 obtained from equation 3A. Clearly equation 4A in the Appendix of the paper represents the complete statement of the problem without any implicit assumptions.

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