An Equivalent pi Network Model for Power System State Estimation with Network Parameter Errors

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***Abstract*—With the role of state estimation in energy management systems gaining weight every day, the demand for its accountability is an imperative, to say the least. The reliability of the network database is thus a key factor. This paper employs the two bus π equivalent model for every line in the power network to approach the network parameter estimation problem. The network π model is known to combine the effect of fixed tap transformers in the equivalent's line impedance and line charging admittances. The method aims to correct the equivalent line parameters of the suspicious branch rather than evaluating every network component individually based on whether there is a transformer or not. The suspicious branch is determined by ranking the branches in order of their respective branch indices obtained in a particular way, from normalized residuals of measurements involved. The technique employs the state vector augmentation approach to correct and store the updated equivalent parameters of the erroneous branch, which is sufficient for an accurate state estimation. Besides this, the correct value of the parameters can always be estimated from the equivalent network if needed.**

Illustrations on the IEEE 14 and 30 bus systems have been furnished to validate the approach for different cases of parameter errors on any single branch.

***Index Terms*— Branch, measurement, parameter error, π equivalent, residual, state estimation, transformer tap.**

I. Introduction

STATE estimation in power systems today holds key to more than for what it was utilized in the initial stages. It has become nothing short of a backbone to the field of energy management studies. It caters to the basic requirement in the system security domain, specifically the contingency analysis. In view of the stated, state estimation bears the heavy responsibility of picturing the state of the system as best and accurate as possible. This in turn shifts focus onto the dependability of fixed data which the state estimation works on. The process of state estimation places huge confidence on the network database which is assumed to be fixed in nature. Hence, any error in the concerned network would culminate in erroneous interpretation which the state estimator would be completely unaware of. If not accounted for, the errors, even small in nature would generate inconsistencies in post-analysis like security assessment.

Network parameters are known to comprise line resistance, reactance, and line charging conductance and susceptance in majority of the cases. Another parameter equally or even more significant in the network is the position of the transformer tap. The lack of communication between the substation and the control center often leads to wrong information of the transformer tap. Thus, the transformer tap too is to be given due attention in this case. Parameter estimation may not boast of abundant literature as it is still constantly evolving into a mature prospect. Still, the literature is not sparse either.

Different methods have contributed towards its cause since days as early as when the concept of the generalized state estimator was introduced [1] and they can be classified broadly into two major groups [2], [3]. The concept of residual analysis [4]-[6] rules one of them and the other is based on augmenting the existing state vector. The residual analysis technique was detailed primarily in [4], wherein, the measurement residuals provide information of existence of gross error. The residual analysis technique is used entirely for the estimation of parameters in [4], [5]. Measurement residuals are also used only to the extent of determining suspicious branches, but not for parameter estimation as such [6]. The state vector augmentation approach [7]-[12] considers the conventional state variables and the suspicious parameters as the combined state vector. The state augmentation can be carried out by either the normal equations method [7]-[10] or the Kalman filter [11], [12], which is a recursive algorithm.

The objective in the present paper is to provide a common platform for parameter estimation on branches with or without transformer taps by using the π equivalent for every branch in the network. The π network's parameters contain the effects of the fixed transformer tap, if any. The idea behind this is to estimate the parameters of the equivalent network, which has only the general elements and no specific tap to estimate. This is specifically useful if the aim is to attain the correct state estimate. The equivalent parameters are updated whenever estimated and are sufficient for accurate state estimation. Besides this, if the original parameter estimates are the need of the hour, the equivalent parameters can always be converted back with ease as shown in a further section.

The equivalent network does not affect the identification and detection of erroneous branches because the method

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employs measurement residuals for the purpose. A branch index based on these residuals, described in a later section, is obtained for each branch. The branches are ranked in order to determine the suspicious one. The equivalent network's parameters are augmented to the state vector using the normal equations method to obtain their estimate. The correct estimated network parameters can also be extracted from the estimates of the equivalent. This paper addresses any type of parameter error on a single branch.

II. Equivalent Model Approach

A. Representation of π Network

A line or branch with a transformer can be represented as the π network. A transformer of ratio 1:a connected between two buses i and j is shown in fig. 1. The transformer is connected to the bus i. The line admittance is given by y_{ij} and the leakage admittance equal on both sides, is given by y_o. Voltage and current are denoted as V and I respectively.

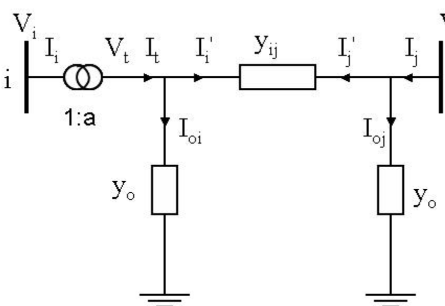

Fig. 1. Transformer on line connecting ends i and j.

Transformer principles would confirm (1) and (2).

$$V_t = aV_i \tag{1}$$

$$I_t = \frac{I_i}{a} \tag{2}$$

Simple Kirchhoff laws would support the voltage current relations for both the sides of the line.

Side *i*:

$$\begin{aligned}\frac{I_i}{a} &= I_i' + I_{oi} \\ &= \left(aV_i - V_j\right)y_{ij} + aV_i y_o \\ I_i &= a\left(aV_i - V_j\right)y_{ij} + a^2 V_i y_o \\ &= a^2 V_i\left(y_{ij} + y_o\right) - ay_{ij}V_j\end{aligned}$$

Adding and subtracting the term $ay_{ij}V_i$ would yield in (3).

$$I_i = V_i\left(a^2 y_o + a\left(a-1\right)y_{ij}\right) + \left(V_i - V_j\right)ay_{ij} \tag{3}$$

Side *j*:

$$\begin{aligned}I_j &= V_j y_o + \left(V_j - aV_i\right)y_{ij} \\ &= V_j\left(y_o + y_{ij}\right) - aV_i y_{ij}\end{aligned}$$

Adding and subtracting the term $ay_{ij}V_j$ would yield in (4).

$$I_j = V_j\left(y_o + \left(1-a\right)y_{ij}\right) + \left(V_j - V_i\right)ay_{ij} \tag{4}$$

The equivalent π network parameters are given by (5) with reference to (3) and (4) respectively. Fig. 2 depicts the equivalent network.

$$\begin{aligned}y^{eq} &= ay_{ij} \\ y_{oi}^{eq} &= a^2 y_o + a\left(a-1\right)y_{ij} \\ y_{oj}^{eq} &= y_o + \left(1-a\right)y_{ij}\end{aligned} \tag{5}$$

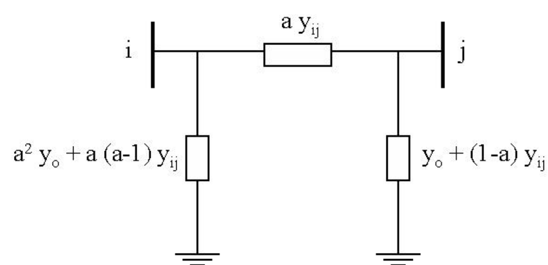

Fig. 2. Equivalent Π Network Representation

Equation (5) can be split into the rectangular components for the requirement of use in state estimation. Equations (6), (7) and (8) depict the same.

$$\begin{aligned}g^{eq} &= ag_{ij} \\ b^{eq} &= ab_{ij}\end{aligned} \tag{6}$$

$$\begin{aligned}g_{oi}^{eq} &= a^2 g_o + a\left(a-1\right)g_{ij} \\ b_{oi}^{eq} &= a^2 b_o + a\left(a-1\right)b_{ij}\end{aligned} \tag{7}$$

$$\begin{aligned}g_{oj}^{eq} &= g_o + \left(1-a\right)g_{ij} \\ b_{oj}^{eq} &= b_o + \left(1-a\right)b_{ij}\end{aligned} \tag{8}$$

If there is no transformer present, a can be replaced the value of 1. If the transformer tap is of the form b:1, the same procedure can be adopted with $a = 1 / b$. If the transformer is on the other end, the ends i and j are interchanged in the same equations.

B. Significance

The equivalent terms given above are used to build the network admittance matrix. The same terms are subjected to parameter estimation process described later. Once estimated, the new values are stored in the database. This removes the necessity of estimating the tap position as a separate entity. The state estimation can be carried out successfully with the equivalent value itself. The model makes true sense when it comes to transformer connected buses.

It is not always necessary to estimate all the six parameters of the equivalent shown in (6), (7) and (8). A transformer is plainly used to shift the voltage level and is generally not a part of a line having line impedance and line charging admittances. Such lines mostly have only the transformer reactance in place. If this is the case, all the six terms mentioned need not be estimated. If this is the case, only the three reactive components would have the transformer effect, and would have to be estimated. On the other hand, if the line has no transformer, the π model would not have different leakage admittances on either side thus reducing the number of parameters to be estimated, to four.

The estimation of the equivalent parameters would yield in the same state estimate as the estimation of the individual parameters. However, if the estimation of the individual parameter is also required, they can always be obtained from the equivalent anytime, as shown in the further section on normal equations method of parameter estimation.

III. Parameter Estimation

A. Detection of Parameter Error

The method employs the normalized measurement residuals [2] to detect any parameter error. A parameter error is analogous to the correlated errors in any of the measurements adjacent to the erroneous branch. These measurements are the power flow on the erroneous branch and the power injections on the end nodes. Thus, the measurement residuals provide the window to lookout for parameter errors as well. The normalized measurement residual, when calculated to be above a threshold value, generally 3.0 [2], indicates an indirect error in the calculation of that measurement due to the actual error in one or more branch parameters related to that measurement. This only detects the error but does not identify the branch. The erroneous branch is identified by the branch index described in the immediately next section.

The residual for a measurement z_i is given by (9). The normalized value is given by (10).

$$r_i = z_i - h_i(\hat{x}) \tag{9}$$

where $\hat{x}$ is the estimated state of the prior state estimation, z_i is the vector of given measurement set and h_i is the vector of calculated measurements. The residuals can be determined only after the state estimation process is done.

$$r_i^N = \frac{|r_i|}{\sqrt{\Omega_{ii}}} \tag{10}$$

Ω is the covariance matrix of the measurement residuals, given in (11).

$$\Omega = R - HG^{-1}H^T \tag{11}$$

where R is the measurement error covariance matrix, H is the measurement Jacobian and G is the state estimation gain matrix.

The measurement residuals detect any error only when there is enough local redundancy. If the measurement is critical in nature, the error in it goes unidentified.

B. Identification by Branch Index

The high normalized residuals need to be linked to the correct branch to ensure correct estimation. The work pertaining to this paper identifies branches by ranking them in order of their respective indices. For a given branch, normalized residuals would arise from its branch flows or the power injections at the end nodes. The approach used here takes into account, all normalized residuals greater than 3.0, pertaining to a branch. The maximum among these is the index of that branch, as shown in (12).

$$\begin{gathered} Index_i = \max\left(r_j^N\right) \\ i \in [1, m],\ j \in \left\{r_j^N > 3.0\right\} \end{gathered} \tag{12}$$

where m is the number of branches and j is corresponding to a measurement associated with the branch i. The branch with the maximum index is chosen to have its parameters estimated.

Critical Tuples

In case, two branches end up with identical values for their indices, the procedure has not been able to clearly identify any one branch. The parameter error could be in either branch. This generally happens in case of critical tuples which has been discussed in [8]. The identical value may also be attributed to the normalized residual of a power injection common to both the branches. In such cases, counter-checking the normalized residuals of the branch flows so as to identify which branch has a higher value may help provided they too are not similar.

C. Estimation by Normal Equations Method

The normal equations method of augmenting the state vector clubs the conventional state variables with the suspicious parameters to be estimated together using the Newton-Raphson technique, as shown in (13).

$$x = \left[x_V, x_\theta \mid x_p \right] \tag{13}$$

where V, θ and p represent voltage magnitude, its angle and parameter respectively.

One area of concern with this approach is regarding the flat start of the variables generally done before the start of the first iteration. The flat start leads to Jacobian singularity on account of last column of the Jacobian turning null very often. To counter this, the parameters are augmented to the state vector after the first iteration.

D. Equivalent and Individual Estimates

The approach in this paper directly gives the final estimates of the equivalent network, given by $y^{eq}, y_{oi}^{eq}, y_{oj}^{eq}$. This would suffice for the purpose of state estimation to yield correct states because at each iterative step, the network admittance matrix is updated with the equivalent element estimates. However, the method is not incapable of updating the individual parameters. The equivalent parameters are nothing but functions of these. Thus, if the equivalent network estimates are given by $k1$, $k2$ and $k3$, the solution of (14) in 3 variables would yield the individual parameter estimates. Any simple non-linear solution technique would yield the required results.

$$
\begin{aligned}
k1 &= a y_{ij} \\
k2 &= a^2 y_o + a\left(a-1\right) y_{ij} \\
k3 &= y_o + \left(1-a\right) y_{ij}
\end{aligned} \tag{14}
$$

This set of equations can be written twice to solve for g and b separately if required.

Transformer Tap

The variable estimated in (14) is a, which may not necessarily be the tap ratio. If the original ratio was inverted to convert to 1:a form for developing this equivalent model, the true estimate would be $1 / a$.

IV. Simulation Results

The technique discussed in the paper thus far has been implemented on standard IEEE 14 and 30 bus systems data [13], the results of which have been furnished in detail below. This paper currently deals with single branch errors. Different types of errors as depicted in the three cases given below have been handled on single branches. The state estimation results after equivalent parameter estimation have been compared with the state estimation results with the parameter errors.

A. IEEE 14 bus system

1) Case I: Single Error on Single Branch

This case deals with introduction of an error in any one of the branch components apart from transformer tap, on a single branch. Table I shows particulars of three different branches having a single error, but not simultaneously. They are three separate cases and are handled individually. The symbols r, x and bs denote line resistance, line reactance and leakage susceptance respectively. The true value and error value are given too.

Table I
Single Error On Single Branch

Branch Subjected To Error	Component in Error	Original Value	Error Value
13-14	r	0.06701	1.06701
7-9	x	0.11001	1.11001
3-4	bs	0	0.7

Table II gives the ranking of the branch indices for each of the three cases. The indices identify the branches distinctly and correctly in each of the three cases.

Table II
Branch Index Ranking

Branch Subjected To Error	Rank of Highest Normalized Residual	Corresponding Branch
13-14	12.5758	13-14
	10.7922	9-14
	10.196	12-13
7-9	6.63021	7-9
	3.75991	4-7
	3.75991	7-8
3-4	6.46194	3-4
	4.8282	2-3
	3.78833	2-4

2) Case II: Multiple Errors on Single Branch

This case deals with introduction of error in more than one component except transformer tap, on a single branch. Table III shows three different branches having errors on r, x and bs at the same time. But only one branch is considered to have the errors.

Table III
Multiple Errors on Single Branch

Branch Subjected To Error	Component in Error	Original Value	Error Value
1-5	r	0.05403	1.05403
	x	0.22304	1.22304
	bs	0.0492	0.2492
2-4	r	0.05811	1.05811
	x	0.17632	1.17632
	bs	0.0374	0.2374
2-5	r	0.05695	1.05695
	x	0.17388	1.17388
	bs	0.034	0.234

Table IV gives the ranking of the branch indices for each of the three cases. The indices identify the branches distinctly and correctly in each of the three cases.

TABLE IV
BRANCH INDEX RANKING

Branch Subjected To Error	Rank of Highest Normalized Residual	Corresponding Branch
1-5	20.3836	1-5
	13.4019	2-5
	13.4019	4-5
2-4	15.3021	2-4
	8.77077	2-3
	8.77077	2-5
2-5	11.2689	2-5
	6.60812	1-5
	6.60812	4-5

3) Case III: Transformer Tap Error on Single Branch

This case deals with introduction of error in the transformer tap and the reactance of a single branch. Table V shows two different branches having the tap error. This case too pertains to one branch at a time.

TABLE V
TRANSFORMER TAP ERROR ON SINGLE BRANCH

Branch Subjected To Error	Component in Error	Original Value	Error Value
4-9	x	0.55618	0.25618
	tap	0.969	0.869
5-6	x	0.25202	0.55202
	tap	0.932	0.862

Table VI gives the ranking of the branch indices for both the cases. The indices identify the correct branch clearly on both occasions.

TABLE VI
BRANCH INDEX RANKING

Branch Subjected To Error	Rank of Highest Normalized Residual	Corresponding Branch
4-9	9.00789	4-9
	6.05973	4-7
	4.56121	7-9
5-6	4.31149	5-6
	2.34741	1-5
	2.34741	2-5

The branches indicated by the branch index based on highest normalized residuals are estimated for their equivalent parameters. Once they are estimated and updated, the state estimation results can be computed. Due to space constraints, the state estimation results for only the case of transformer tap error in branch 4-9 from Table V have been shown. Table VII compares the state estimation results obtained when there is no error with those obtained with error and corrected equivalent parameters.

TABLE VII
STATE ESTIMATION RESULTS

	No Error		With Error		Estimated	
Bus	V	θ	V	θ	V	θ
1	1.06	0	1.00439	0	1.06	0
2	1.045	-4.97895	0.988044	-5.54695	1.045	-4.97895
3	1.01	-12.7128	0.951511	-14.226	1.01	-12.7128
4	1.01862	-10.3201	0.958757	-11.5462	1.01862	-10.3201
5	1.02026	-8.77904	0.963251	-9.77973	1.02026	-8.77904
6	1.07	-14.2169	1.03053	-15.0642	1.07	-14.2169
7	1.06195	-13.3629	1.03727	-13.9027	1.06195	-13.3629
8	1.09	-13.3629	1.06805	-13.8438	1.09	-13.3629
9	1.05635	-14.9406	1.04488	-15.2161	1.05635	-14.9406
10	1.05133	-15.0983	1.03564	-15.4504	1.05133	-15.0983
11	1.05708	-14.7893	1.03049	-15.4033	1.05708	-14.7893
12	1.05522	-15.0714	1.01718	-16.0106	1.05522	-15.0714
13	1.05044	-15.1529	1.0137	-16.0458	1.05044	-15.1529
14	1.03579	-16.0325	1.01176	-16.5925	1.03579	-16.0325

Table VII shows clearly that the state estimation results after the estimation of equivalent parameters are the same as without the error. In addition, when (14) is solved for these numerous cases given above, the individual parameters match exactly with the original values mentioned in the tables.

B. IEEE 30 bus system

1) Case I: Single Error on Single Branch

Table VIII shows particulars of three different branches having a single error, but not simultaneously. They are three separate cases and are handled individually.

TABLE VIII
SINGLE ERROR ON SINGLE BRANCH

Branch Subjected To Error	Component in Error	Original Value	Error Value
2-4	r	0.0570	1.0570
4-6	x	0.0414	1.0414
29-30	bs	0	0.5

Table IX gives the ranking of the branch indices for each of the three cases. The indices do not identify the branches distinctly in the case of error in the leakage susceptance of branch 29-30.

Identical Normalized Residuals:

The maximum normalized residuals of both branches 27-30 and 29-30 are identical. This is due to the maximum residual arising from the common power injection at bus 30. Bus 30 is connected to only two buses 27 and 29. So, the power injection at bus 30 is a measurement adjacent to both buses 27 and 29. However, on comparing the normalized residuals of the branch flows on the two branches, the branch flow on 29-30 has a normalized residual greater then 8 whereas that on branch 27-30 has just above 0.5. It is clear from this that the erroneous branch is 29-30.

TABLE IX
BRANCH INDEX RANKING

Branch Subjected To Error	Rank of Highest Normalized Residual	Corresponding Branch
2-4	11.9403	2-4
	7.78801	3-4
	7.78801	4-6
4-6	20.2966	4-6
	11.7725	3-4
	11.7725	4-12
29-30	8.69994	29-30
	8.69994	27-30
	8.47777	27-29

2) Case II: Multiple Errors on Single Branch

This case deals with introduction of error in more than one component except transformer tap, on a single branch. Table X shows three different branches having errors on *r*, *x* and *b*s at the same time. But only one branch is considered to have the errors.

TABLE X
MULTIPLE ERRORS ON SINGLE BRANCH

Branch Subjected To Error	Component in Error	Original Value	Error Value
2-5	r	0.0472	1.0472
	x	0.1983	1.1983
	bs	0.0418	0.2418
6-7	r	0.0267	1.0267
	x	0.0820	1.0820
	bs	0.0170	0.2170
6-28	r	0.0169	1.0169
	x	0.0599	1.0599
	bs	0.0130	0.2130

Table XI gives the ranking of the branch indices for each of the three cases. The indices identify the branches distinctly and correctly in each of the three cases.

TABLE XI
BRANCH INDEX RANKING

Branch Subjected To Error	Rank of Highest Normalized Residual	Corresponding Branch
2-5	21.6674	2-5
	16.5677	5-7
	12.786	2-4
6-7	10.6371	6-7
	7.97217	5-7
	5.53609	2-6
6-28	5.42177	6-28
	3.44432	8-28
	3.44432	28-27

3) Case III: Transformer Tap Error on Single Branch

Table XII shows two different branches having the tap error. This case too pertains to one branch at a time.

TABLE XII
TRANSFORMER TAP ERROR ON SINGLE BRANCH

Branch Subjected To Error	Component in Error	Original Value	Error Value
4-12	x	0.2560	0.5560
	tap	0.932	0.832
6-10	x	0.5560	0.2560
	tap	0.969	0.869

Table XIII gives the ranking of the branch indices for both the cases. The indices identify the correct branch clearly on both occasions.

The branches indicated by the branch index based on highest normalized residuals are estimated for their equivalent parameters. Due to space constraints, the state estimation results for only the case of transformer tap error in branch 4-12 from Table XII have been shown. Table XIV compares the state estimation results obtained when there is no error with those obtained with error and corrected equivalent parameters.

TABLE XIII
BRANCH INDEX RANKING

Branch Subjected To Error	Highest Normalized Residual	Corresponding Branch
4-12	5.0062	4-12
	2.85563	2-4
	2.85563	3-4
6-10	10.0644	6-10
	5.64865	6-9
	4.38077	9-10

TABLE XIV
STATE ESTIMATION RESULTS

	No Error		With Error		Estimated	
Bus	V	θ	V	θ	V	θ
1	1.05997	0	1.04273	0	1.05996	0
2	1.04297	-5.34816	1.02515	-5.51571	1.04296	-5.3482
3	1.02068	-7.52967	1.00146	-7.69074	1.02067	-7.52976
4	1.01169	-9.28128	0.991674	-9.44705	1.01169	-9.28141
5	1.00997	-14.1623	0.991864	-14.645	1.00996	-14.1624
6	1.0102	-11.0616	0.991897	-11.4469	1.01019	-11.0617
7	1.00233	-12.8618	0.983997	-13.2959	1.00232	-12.8619
8	1.00997	-11.8105	0.991664	-12.2129	1.00996	-11.8106
9	1.05084	-14.1068	1.04116	-15.0713	1.05084	-14.1064
10	1.04505	-15.6973	1.03891	-16.8562	1.04505	-15.6966
11	1.08195	-14.1072	1.07328	-15.1103	1.08195	-14.1067
12	1.05708	-14.9378	1.06591	-17.2433	1.05708	-14.9362
13	1.07097	-14.9378	1.07906	-17.1475	1.07098	-14.9362
14	1.04224	-15.829	1.04972	-17.8828	1.04224	-15.8274
15	1.03765	-15.9201	1.04344	-17.8765	1.03766	-15.9186
16	1.04433	-15.5226	1.0463	-17.2031	1.04433	-15.5214
17	1.03983	-15.859	1.03535	-17.1524	1.03983	-15.8582
18	1.0281	-16.5369	1.02914	-18.1825	1.0281	-16.5358
19	1.02559	-16.7117	1.02443	-18.2237	1.02559	-16.7107
20	1.02967	-16.5155	1.02761	-17.9678	1.02967	-16.5146
21	1.03208	-16.161	1.02579	-17.3409	1.03208	-16.1603
22	1.03428	-16.0829	1.02895	-17.3209	1.03428	-16.0822

23	1.02723	-16.3038	1.02941	-18.0118	1.02723	-16.3026
24	1.02188	-16.4669	1.01786	-17.8022	1.02188	-16.4661
25	1.01736	-16.0504	1.00849	-17.0302	1.01736	-16.05
26	0.999619	-16.4711	0.990864	-17.4414	0.999617	-16.4707
27	1.02322	-15.5303	1.01181	-16.3191	1.02322	-15.5301
28	1.00677	-11.6849	0.988792	-12.1027	1.00676	-11.6849
29	1.00338	-16.7601	0.99247	-17.6118	1.00338	-16.7599
30	0.991903	-17.6426	0.981041	-18.5183	0.991902	-17.6424

Table XIV shows clearly that the state estimation results after the estimation of equivalent parameters are very similar to those without the error. In addition, when (14) is solved for these numerous cases given above, the individual parameters match exactly with the original values mentioned in the tables.

V. Conclusion

The paper motivates the idea of employing a π equivalent network for every branch in the system for state estimation of a system affected by branch parameter and transformer tap errors. The equivalent network provides a common structure for network lines and transformer branches as it includes the transformer effect in the equivalent branches. The parameter estimation algorithm estimates the correct equivalent parameters rather than correcting the original network parameters and taps separately. However, if the individual parameter estimate values are also required, the estimates of the equivalent can readily be used to estimate the parameters. Illustrations of the method are provided on IEEE 14 and 30 bus systems for different scenarios including one case of identical values of normalized residuals. This paper caters to single branch errors. The authors are presently working towards catering to errors in multiple and adjoining branches and that work will be published in future.

VI. References

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VII. Biographies

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