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STEAM DATA VERIFICATION AND TROUBLESHOOTING TECHNIQUE

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Abstract—A steam data/meter verification and troubleshooting technique has been developed and implemented to help determine erroneous data in the steam balance report and identify faulty meters or errors in data transmission. This includes an analytical technique which utilizes redundancy in existing steam flow measurements and a diagnostic tree which uses the result of physical checking of the suspect flow meters/data in a sequential manner until fault diagnosis is completed.

The important features of this technique are (1) it is based on the concept of diagnosibility rather than blindly applying an analytical technique to identify faulty meter(s), (2) the ability to identify all the probable sets of faulty flow meters, (3) the corrected flow data are available once the faulty flow meter(s) are determined, (4) relatively small amount of calculation is needed, and (5) a diagnostic tree is used to guide physical checking of the suspect flow meter(s) until diagnosis is completed.

INTRODUCTION

As a result of increased emphasis on cost reduction and energy accountability, it is important to maintain the integrity of the plant steam balance. Plant steam data had been usually examined daily by Process engineers. Suspect data and flow meters had been identified in a weekly meeting with Plant Engineering; then Maintenance people check the suspect meters. This process was very tedious, time consuming and often not successful in identifying meter problems. In order to reduce time and effort necessary for steam data/meters verification and troubleshooting, there had been a strong need for an analytical technique which utilizes redundancy in existing steam network.

This steam data/meter verification and troubleshooting technique was designed to help determine erroneous data in the steam balance report and identify faulty meters or errors in data transmission. This includes an analytical technique which utilizes redundancy in existing steam flow measurements and a diagnostic tree which uses the result of physical checking of the suspect flow meters/data in a sequential manner until fault diagnosis is completed.

A number of methods of gross error detection have appeared in literature [1-16]. Most of these involve the use of statistical tests based on assumption that the random errors in the data are normally distributed. Most recently Serth and Heenan [17] compared the performance of different algorithms reported in the literature using computer simulation.

In this paper, a practical steam data verification technique, which has been used in a real plant for the last five years, is discussed. The important features of this technique are (1) it is based on the concept of diagnosibility rather than blindly applying an analytical technique to identify faulty meter(s)/data, (2) the ability to identify all the probable sets of faulty flow meter(s)/data, (3) the corrected flow data are available once the faulty flow meter(s)/data are determined, (4) relatively small amount of calculation is needed, and (5) a diagnostic tree is used to guide physical checking of the suspect flow meter(s)/data until diagnosis is completed.

NODAL REPRESENTATION OF A STEAM NETWORK

One of the distinct characteristics of a plant steam system is that it represents a complex network of many interacting streams. In a typical plant there can be hundreds of steam flows, some of them metered and others unmetered. Among the unmetered steam flows, many may remain fairly constant and can be estimated. To write an appropriate material balance for each piece of equipment using these metered and/or

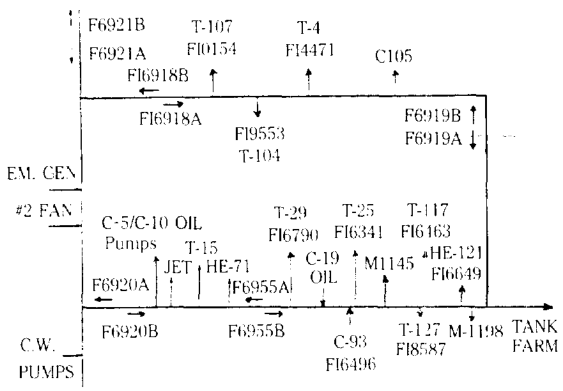


Fig. 1. Area I 160# steam network.

unmetered flows and handling the resulting equations simultaneously in one grand swoop is not only unnecessary but also expensive.

The plant steam network can be broken up into smaller, more manageable subsystems for ease of analysis. The approach chosen here is to subdivide the plant steam network into several different subnetworks based on pressure levels of steam and the different areas of the plant.

A node is defined as a subsystem of a network around which a mass balance can be made using either metered or estimated flows. This is perhaps best explained with an example. Figure 1 shows the 160# steam network in Area I in a Plant. Four independent material balances can be made in the steam network in Figure 1. This steam network can be redrawn using nodal representation as in Figure 2. In Figure 2, input/output from each node and the relationship between nodes can be clearly seen. All the streams shown in Figure 2 are either metered or a fairly good estimate is normally available. Therefore these four material balance equations provide redundancy of information to this system and enable fault detection and diagnosis to some extent.

Before we start to use any mathematical techniques to detect and diagnose steam data imbalances, we have to reduce the number of streams by combining the different streams connecting two different nodes or connecting a node and the environment. Figure 3 shows the reduced nodal representation of the steam system in Figure 2. Note that there is only a single stream between two different nodes and between a node and the environment. Figure 4 shows the actual data for the reduced nodal representation in Figure 3.

No matter which mathematical technique is used, any diagnosis of each combined flow into its constituent flows is not possible without actually checking each flow meter or estimated flow. Therefore any ma-

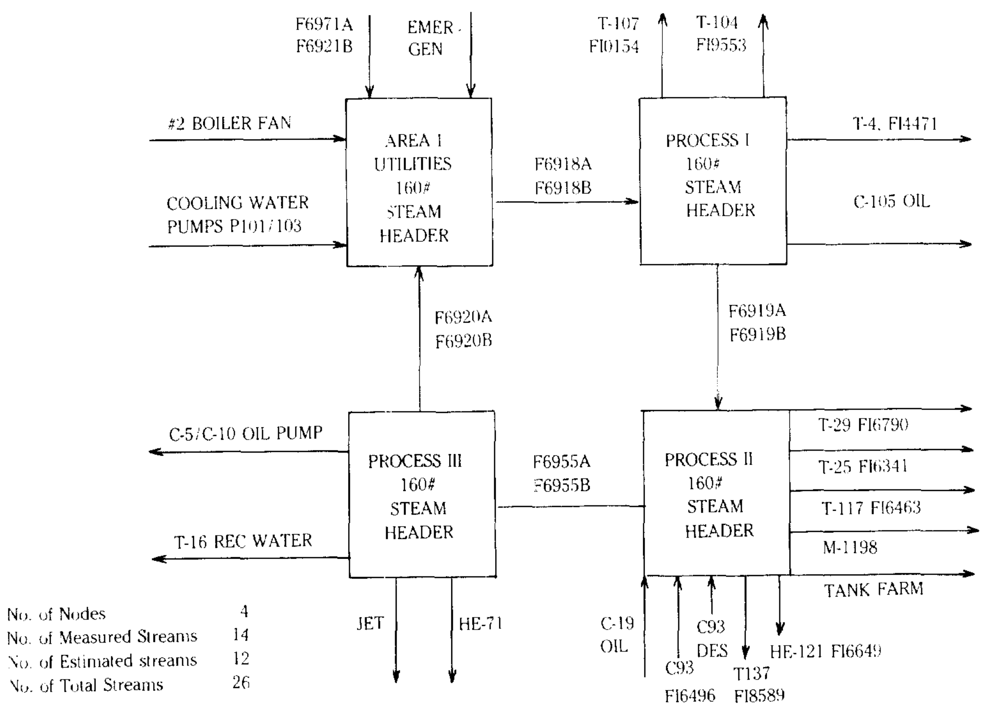
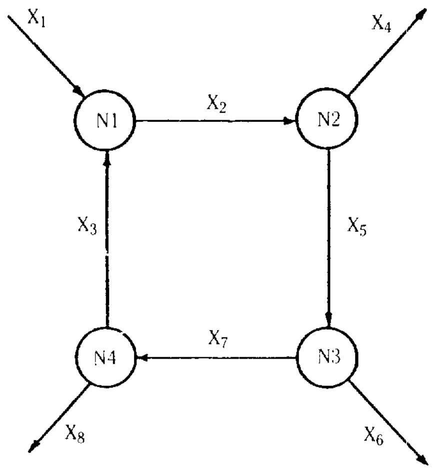


Fig. 2. Nodal representation of Area I 160# steam network.

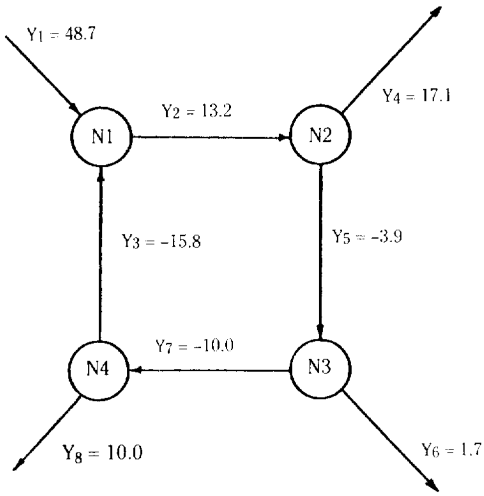


where $X_1 = M1 + E1 + E2 + E3$
$X_2 = M2$
$X_3 = M3$
$X_4 = M4 + M5 - M6 + E4$
$X_5 = M7$
$X_6 = M8 + M9 - M10 + E5 + E6 + M11 + M12 - E7 - M13 - E8$
$X_7 = M14$
$X_8 = E9 + E10 - E11 + E12$

Material balances exist as

$X_1 + X_3 - X_2 = 0$
$X_2 - X_4 - X_5 = 0$
$X_5 - X_6 - X_7 = 0$
$X_7 - X_3 - X_8 = 0$
$X_1 - X_4 - X_6 - X_8 = 0$

Fig. 3. Reduced nodal representation of Area I 160# steam network.



where $Y_1 = YM1 + YE1 + YE2 + YE3$
$Y_2 = YM2$
$Y_3 = YM3$
$Y_4 = YM4 + YM5 + YM6 + YE4$
$Y_5 = YM7$
$Y_6 = YM8 + YM9 + YM10 + YE5 + YE6 - YM11 + YM12 - YE7 - YM13 - YE8$
$Y_7 = YM14$
$Y_8 = YE9 + YE10 + YE11 + YE12$

Fig. 4. Area I 160# steam data on August 11, 1981.

thematical techniques for diagnosis should be used after the reduced nodal representation of the steam system is prepared.

STRUCTURE OF THE STEAM NETWORK AND FAULT DIAGNOSIBILITY

The structure of the system determines fault diagnosibility (to what extent we can diagnose the cause of the fault analytically). Any diagnosis with analytical techniques is possible due to the existence of some redundancy in the system structure.

With analytical techniques we can determine if any faults exist in a system and narrow the scope or reduce the number of probable solutions for diagnosis. Sometimes we may isolate a unique faulty flow or set of faulty flows but most often we end up with several probable solutions for diagnosis using analytical techniques. Thus in these cases fault diagnosis must be completed by physically checking the suspect flow data/meter(s).

The information about the individual flows which make up each material balance in a same combination cannot be isolated analytically. The flows should be treated as a single flow (combined flow) analytically. Once a combined flow is found to be faulty, at least one of its constituent flows is faulty. Even though a combined flow is found normal, it does not rule out the possibility that there may exist offsetting faults among the flows making up the combined flow.

Because of the redundancy requirement the maximum number of simultaneous faulty flow meters/data which can be identified is one less than the number of independent material balance equations. For example, if the number of independent material balance equations is four as the steam system shown in Figure 3, the maximum number of simultaneous erroneous meters/data we can identify using this technique is three.

The probability of occurrence of two simultaneous faults is much less than that of one fault and the probability of occurrence of three simultaneous faults is much less than that of two simultaneous faults. Especially in a real situation such as a plant where the faulty meters are continuously identified and repaired. But still there is a possibility of two or three simultaneous erroneous meters/data. Thus even though a potentially erroneous meter is identified from a single fault assumption, it is worthwhile to check to see if two or three simultaneous erroneous meters/data can result in the same set of data.

MODELLING OF FLOW MEASUREMENT WITH ERRORS

If we define X_i as the true flow of the stream i and Y_i as the measurement of X_i, then

$$Y_i = X_i + r_i + b_i \tag{1}$$

where r_i is the random error of measurement at normal conditions and b_i is the bias error (or gross error) due to faulty meter or data communication problem.

In Figure 2, M_j and E_k represent the true flow of metered stream and unmetered stream. YM_j and YE_k indicate the measurement of flow j and estimate of flow k, respectively. Generally a combined measurement can be calculated as

$$Y_i = \sum_j YM_j + \sum_k YE_k \tag{2}$$

and the standard deviation for a combined measurement at normal conditions can be calculated from individual standard deviation of measurement YM_j or of estimate YE_k at normal conditions as follows:

$$s_{y_i} = \text{SQRT}\left(\sum_j s_{YM_j}^2 + \sum_k s_{YE_k}^2 \right) \tag{3}$$

A nodal imbalance is defined as the difference between the sum of the incoming flows and the sum of the outgoing flows from the node.

$$NB_i = \sum_l (\text{flow into } i^{th} \text{ node})_l$$

$$- \sum_m (\text{flow out from } i^{th} \text{ node})_m \tag{4}$$

where NB_i is i th nodal imbalance. And the standard deviation of NB_i at normal condition can be calculated as

$$s_{NB_i} = \text{SQRT}\left(\sum_j s_{Y_j}^2 \right) \tag{5}$$

FAULT DETECTION

The first step in identifying faulty flow meters/data is to determine whether there is any abnormal inconsistency in a set of data from the steam system. Each one of the nodal imbalances should be checked with its threshold limit (TL) to determine whether all of the nodal imbalances (NB) are within normal ranges. If $|NB_i| \leq TL_i$, for all i, decide all the flow meters/data are normal, otherwise decide at least one of the flow meters/data is faulty.

As the threshold limit increases, the probability of correct decision increases when there is no bias error (see Figure 6) but decreases when there is a bias error

	X1	X2	X3	X4	X5	X6	X7	X8
N1*	1	-1	1					
N2		1		-1	-1			
N3*					1	-1	-1	
N4*			-1				1	-1
NT	1			-1		-1		-1

Fig. 5. Incidence marix of the example steam network.

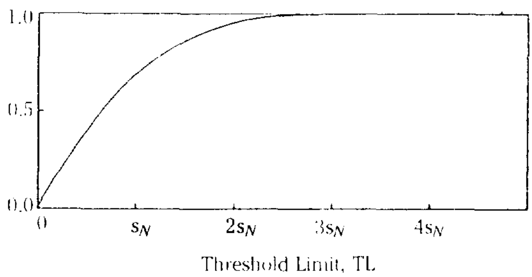


Fig. 6. Probability of correct decision when there is no error.

(see Figure 7). With a large threshold limit, only big bias errors can be detected and the probability of correct decision is high when there is no bias error. On the other hand, with a small threshold limit, small bias errors can be detected but also the probability of wrong decision is high when there is no error.

Proper threshold limits should be determined depending on an analysis of the tradeoffs between two types of wrong decisions (deciding faulty when normal and deciding normal when faulty), rather than blindly using three standard deviations as threshold limits. In steam network problems the cost of deciding faulty when actually normal is the cost of diagnosis effort to locate the faulty flow meters or data. The cost of deciding normal when actually faulty is the degradation of steam data and poor accountability.

If the threshold limit is chosen to be the same size as s_N (one standard deviation of the nodal imbalance at

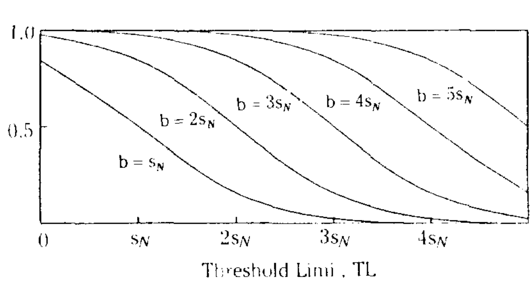


Fig. 7. Probability of correct fault detection vs. threshold limit for different sizes of bias errors.

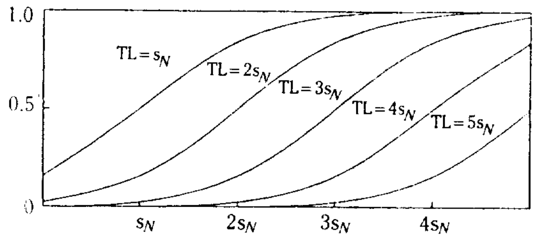


Fig. 8. Probability of correct fault detection vs. size of bias error for different threshold limit.

normal condition), the probability of the correct decision is 0.68 when there is no bias error and 0.84 when the size of the bias error is $2s_N$. If the threshold limit is $2s_N$, the probability of the correct decision is 0.95 when there is no bias error and 0.5 when the size of the bias error is $2s_N$ (See Figure 7). For a constant threshold limit, the probability of correct decision increases as the size of the bias error increases (See Figure 8).

FAULT DIAGNOSIS

Once it is decided that at least one of the flow meters/data is faulty, a fault diagnosis should follow to find which flow meter(s) or data are in error and what are the correct values of the flows. The technique we have been using since 1981 has been recently classified as a combinatorial technique by Seith and Heenan [17]. The basic idea is to find all the analytically possible solutions which can result in the given data. Once all the possible solutions are identified, physical checking is done in the sequence of the most probable suspect until diagnosis is completed.

Basic Analytical Diagnosis Procedure

The existing analytical redundancy in steam flow measurements can make fault diagnosis possible to a certain degree. The degree of fault diagnosis depends on the structure of the steam system, which determines the analytical redundancy.

The method used here is a procedure of (1) successively making a series of assumptions on flow meters/data, (2) calculating estimates of the flows for the data which was assumed erroneous by using the data which was assumed correct and the material balance equations, and (3) checking each assumption to see if all the material balance constraints are satisfied by the data assumed correct and the calculated flows.

Sometimes only one assumption can lead to satisfaction of all constraints. In this case the fault diagnosis is complete. But in most cases more than one assumption can lead to satisfaction of all the constraints and fault diagnosis cannot be completed without actually checking each of these possibilities in the field.

The basic fault diagnosis procedure is as follows:

a. Assume a single fault

(1) Assume only Y_1 is in error, which means

$b_1 \neq 0,\ b_2 = b_3 \cdots = b_n = 0.$

Calculate the estimate of X_1 using one material balance equation and other measurements.

Check if each nodal imbalance is less than its threshold limit when X_1 substitutes for Y_1.

If all the nodal imbalances are less than their respective threshold limits, this assumption may be correct. If any one of the nodal imbalances is bigger than its threshold limit, this assumption is wrong.

(2) Repeat (1) for $Y_2, Y_3, \cdots, Y_n$.

b. Assume a double fault

(1) Assume Y_1 and Y_2 are in error, which means

$b_1 \neq 0,\ b_2 \neq 0,\ b_3 = \cdots = b_n = 0$

Calculate X_1 and X_2 using two material balance equations and other measurements. Check if each nodal imbalance is less than its threshold limit when X_1 and X_2 substitute for Y_1 and Y_2.

If all the nodal imbalances are less than their respective threshold limits, this assumption is one of the possible solutions. If any one of the nodal imbalances is bigger than its threshold limit, this assumption is wrong.

(2) Repeat (1) for all combinations of two flows.

c. Repeat the same procedure in step a or b under the assumptions of up to (m-1) simultaneous faults where m is the number of independent material balances for the steam system. More than (m-1) simultaneous faults cannot be diagnosed using any analytical techniques as the redundancy of information for diagnosis does not exist any more.

If the first possible solution has been found under the assumption of i simultaneous faults, usually it is enough to repeat the same procedure up to the (i+1) simultaneous faults assumption because the probability of occurrence decreases very rapidly with the number of simultaneous faults.

Use of Incidence Matrix to Screen Assumption to be Checked

To save calculations for diagnosis, the result of nodal imbalance tests for fault detection and an incidence matrix of the material balance equations can be used to select assumptions necessary to be checked. An incidence matrix of the material balance equations of the steam system in Figure 3 is shown in Figure 4.

In the incidence matrix in Figure 4 if a variable appears in the material balance equation for a node it is denoted with 1, otherwise left blank. Note all the flows appear twice in the incidence matrix. "*" denotes the nodes whose nodal imbalances exceed their threshold limits.

This incidence matrix is very useful for selecting the assumptions to be tested to determine whether they are viable solutions or not. From this incidence matrix it is clear that to cause imbalance in node 1, at least one of X_1, X_2 and X_3 must be faulty, and if flow meter 1 is faulty it can cause imbalance in both node 1 and total material balance.

It is obvious from the incidence matrix that any single fault cannot cause imbalance in more than two nodes. Thus we need not even check single fault assumptions in this example because more than two nodes are imbalanced. For double faults, only those pairs of measurements need to be tested which affect all asterisked nodes (imbalance exceeds threshold limit). Likewise for triple faults, only those triplets of measurements need be tested which affect all asterisked nodes.

Table 3 shows the assumptions on the number of simultaneously faulty flows to be checked when the number of imbalanced material balances varies from zero to five for a system with four nodes. A computer program has been written to facilitate the selection of the assumptions on the faulty flows before the assumptions are checked.

Physically Checking the Suspect Flow Meters Using a Diagnostic Tree

Once all of the candidate solutions for diagnosis are found by the above method, physical checking of those flow meters should follow to complete fault diagnosis. The selection of the flow meter to be checked first may be determined by using historical reliability data on the flow meters. Those with highest probability of being faulty should be checked first to reduce the time and effort for correct diagnosis. Also the flow meters included in the set of least number of simultaneous faults should be checked first because the probability of the occurrence of multiple faults without common cause decreases drastically as the number of simultaneous faults increases.

Whenever a flow meter (data) is checked, the result of the check can be used in a sequential manner to reduce the number of probable alternative solutions for diagnosis. This procedure can be facilitated by using a diagnostic tree. A diagnostic tree for the example with six sets of probable solutions for diagnosis is shown in Figure 9.

In Figure 9, "( )" indicates each one of the probable solutions for diagnosis, "○" indicates checking the flow meter (data) in it. If the flow meter (data) checked in the circle is found faulty "Faulty" is assigned on the arrow, otherwise "Normal". Finally "( )" indicates that fault diagnosis is completed and flow meters

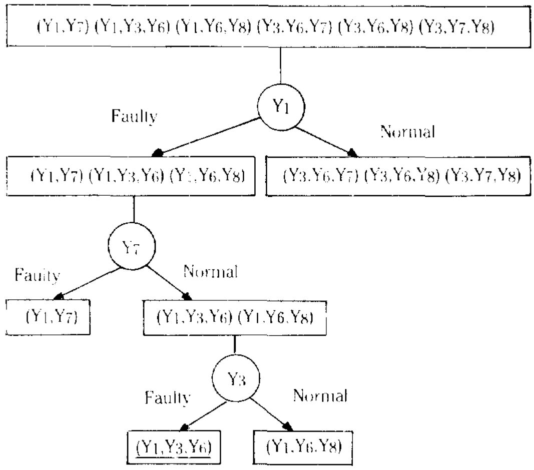


Fig. 9. Diagnostic tree for the example.

(data) in "( )" are found faulty. Fault diagnosis can be completed by checking two or three flow meters (data) in this example. Once the faulty flows are identified, the corrected flows can be calculated from the correct flows.

APPLICATION TO A PLANT STEAM SYSTEM

The fault detection and diagnosis procedure will be illustrated through an operating plant's steam system in Figure 1. Combined measurements in Figure 4 were calculated with the data on August 11, 1981.

The standard deviation of combined measurement Y_i at normal condition can be calculated using equation (3) from individual standard deviation of measurement YM_i in Table 1 and of estimate YE_i in Table 2 as follw:

$s_{Y_1} = 1.7$
$s_{Y_2} = 1.0$
$s_{Y_3} = 1.2$
$s_{Y_4} = 0.38$
$s_{Y_5} = 1.60$
$s_{Y_6} = 3.55$
$s_{Y_7} = 1.01$
$s_{Y_8} = 0.58$

The standard deviation of nodal imbalances at the normal condition can be calculated from equation (5) from individual standard deviation of measurement Y_i.

$s_{NB_1} = 2.31$
$s_{NB_2} = 1.23$
$s_{NB_3} = 3.74$
$s_{NB_4} = 1.67$
$s_{NB_T} = 4.00$

Depending on the up/down status of each equipment in the plant, the values of standard deviation of each

Table 1. Measured flows in Area I 160# steam system.

Flow	Meter	Range (MPPH)	s_M = 2% of Span
M1*	F6921A	0– 75.0	1.50
	F6921B	0– 28.1	0.562
M2*	F6918A	0– 50.0	1.00
	F6918B	0– 37.1	0.744
M3*	F6920A	0– 35.1	0.704
	F6920B	0– 60.0	1.20
M4	FI0154	0– 7.2	0.144
M5	FI9553	0– 15.0	0.304
M6	FI4471	0– 9.2	0.184
M7*	F6919A	0– 30.1	0.602
	F6919B	0– 30.1	0.602
M8	FI6790	0– 14.0	0.280
M9	FI6341	0– 7.0	0.140
M10	FI6463	0– 30.0	0.600
M11	FI6649	0– 5.0	0.10
M12	FI8589	0–120.	2.40
M13	FI6496	0–120.	2.40
M14*	F6955A	0– 50.2	1.00
	F6955B	0– 50.2	1.00

Note: One standard deviation of each measured flow is assumed to be 2% of the span of each flow.
"*" indicates bidirectional flow meter. One of A & B flow is zero.

Table 2. Unmetered flows in Area I #160 steam system.

Flow No.	Description	Design value	Status	s_{E_i}
E1	Emer. Gen.	8.0	On	0.8
E2	#2 Boiler Fan	8.0	Off	0.8
E3	Pond Pumps	28.0	On	2.8
E4	C105 Lube	1.0	Off	0.1
E5	M1198 Jet	1.0	On	0.1
E6	Tank Farm	5.0	On	0.5
E7	C93 Dsprhtr	6.0	On	0.6
E8	C19	35.0	Off	3.5
E9	HE71	4.0	On	0.4
E10	Jet	1.0	On	0.1
E11	T16 Res Water	1.0	On	0.1
E12	C5/C10 Lube	4.0	On	0.4

Note: Each of the above unmetered flows are assumed to have a normal distribution with its design value as a mean and a 10% of its estimate as its standard deviation.

Table 3. No. of simultaneously faulty flows to be diagnosed vs. No. of imbalanced material balances for a system with four nodes.

No. of Imbalanced Material Balances	0	1	2	3	4	5
No. of Simultaneously Faulty Flows	0	1,2	1,2,3	2,3	2,3	3

combined measurement and each nodal imbalance at normal condition should be changed. Nodal imbalances are as follow:

$NB_1 = Y_1 + Y_3 - Y_2 = 19.75$
$NB_2 = Y_2 - Y_4 - Y_5 = -0.05$
$NB_3 = Y_5 - Y_6 - Y_7 = 4.40$
$NB_4 = Y_7 - Y_3 - Y_8 = -4.2$
$NB_T = Y_1 - Y_4 - Y_6 - Y_8 = 19.9$

If we choose one standard deviation of each nodal imbalance at normal condition as the threshold limit of each node we get the following:

$TL_1 = s_{NB_1} = 2.31$
$TL_2 = s_{NB_2} = 1.23$
$TL_3 = s_{NB_3} = 3.74$
$TL_4 = s_{NB_4} = 1.67$
$TL_T = s_{NB_T} = 4.00$
$|NB_1| = |19.75| > TL_1$ unsatisfied
$|NB_2| = |-0.05| < TL_2$ satisfied
$|NB_3| = |4.4| > TL_3$ unsatisfied
$|NB_4| = |-4.2| > TL_4$ unsatisfied
$|NB_T| = |19.9| > TL_T$ unsatisfied

Because $|NB_1|$, $|NB_3|$, $|NB_4|$ and $|NB_T|$ are not less than their threshold limits, it can be decided that there exist at least two faulty meters of data.

Fault diagnosis can be done as follows:

If we assume a double fault two pairs of flows (1,7) and (3,6) can cause imbalance in nodes N_1, N_3, N_4 and N_T. Further analysis by the analytical procedure will show that only (1,7) is a possible solution for diagnosis from a double fault assumption.

If we assume a triple fault, eighteen sets of three flows can cause imbalance in nodes N_1, N_3, N_4 and N_T.

(1,3,5) (1,3,6) (1,5,8) (1,6,8)
(2,3,6) (2,4,7) (2,5,8) (2,6,7) (2,6,8) (2,7,8)
(3,4,5) (3,4,6) (3,4,7) (3,5,6) (3,5,8) (3,6,7)
(3,6,8) (3,7,8)

Further analysis by the analytical procedure will show that from the triple fault assumption the following five sets of flows are possible solutions for diagnosis:

(1,3,6) (1,6,8) (3,6,7) (3,6,8) (3,7,8).

Analytically any one of the six sets of flows are possible solutions for diagnosis. Fault diagnosis can be completed by physically checking the meters/data foll-

Table 4. Probable solutions for diagnosis of the example.

Suspected flows / Estimated flows	Y_1,Y_7	Y_1,Y_3,Y_6	Y_1,Y_6,Y_8	Y_3,Y_6,Y_7	Y_3,Y_6,Y_8	Y_3,Y_7,Y_8
$\hat{X}_1$	28.95*	33.15*	28.95*	48.7	48.7	48.7
$\hat{X}_2$	13.15	13.15	13.15	13.15	13.15	13.15
$\hat{X}_3$	-15.80	-20.00*	-15.80	-35.55*	-35.55*	-35.55*
$\hat{X}_4$	17.10	17.10	17.10	17.10	17.10	17.10
$\hat{X}_5$	-3.90	-3.90	-3.90	-3.90	-3.90	-3.90
$\hat{X}_6$	1.70	6.10*	6.10*	21.60*	6.10*	1.70
$\hat{X}_7$	-5.60*	-10.00	-10.00	-25.55*	-10.00	-5.60*
$\hat{X}_8$	10.00	10.00	5.80*	10.00	25.55*	29.90*

Note: "*" indicates the corrected flows.

owing the diagnostic tree in Figure 9.

This procedure has been programmed and implemented for the entire plant since August, 1982.

NOMENCLATURE

- b_i : bias error in Y_i
- E_k : true flow of estimated (unmetered) flow k
- M_j : ture flow of metered flow j
- NB_i : nodal imbalance of node i
- r_i : random error in Y_i
- S_{NB_i} : standard deviation of NB_i at normal condition
- S_{Y_i} : standard deviation of Y_i at normal condition
- S_{YE_k} : standard deviation of YE_k at normal condition
- S_{YM_j} : standard deviation of YM_j at normal condition
- TL_i : threshold limit of node i
- X_i : true flow of stream i
- Y_i : measurement of stream i
- YE_k : estimate of E_k
- YM_j : measurement of M_j

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