AIRCRAFT ELECTRICAL MONITORING & FAULT DETECTION

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Abstract: Fault detection and electrical system monitoring (management) for aircraft/spacecraft dc or 400 Hz electrical systems is presented. Real-time 'snapshot' data is collected from current and voltage measurement transducers on radial or loop aircraft electrical system and introduced into a State Estimator. The State Estimator 'smoothes' the data, detects bad transducers, and calculates the best estimate of the voltage and phase angle at busses of the network, i.e., the 'state' of the network. Experimental results of estimation and fault detection are presented.

1 INTRODUCTION

Commercial aircraft and NASA spacecraft employ distributed generation/load points and limited transducer monitoring. Recent air disasters such as the Sept. 2, 1998 Swiss Air flight 111 and the July 7, 1996 TWA flight 800 crashes have implicated the electrical system. The FAA has listed 26 reports of accidents or serious electrical system incidents since 1983. Some of these electrical system problems could have been avoided if the aircraft were equipped with improved monitoring and fault detection.

Present day aircraft and aerospace vehicles contain many kilometers of wire throughout the fuselage, wings, and tail structure. A military aircraft may contain 20 kilometers, and a commercial aircraft on the order of 240 km of wire. The wires run through stringers, bulkheads, engine pods and compartments, into the cockpit, wheel-wells, behind panels, etc. Most of the wires are in harnesses, and the terminals are inaccessible unless panels are opened. The wires are subject to fraying in maintenance operations, contacts corrode at high altitudes, insulation degrades due to time or weather. All are faults in the wiring.

Electrical system monitoring instruments presented to the pilots have up to this time generally been analog-type, and very limited in number. The pilot's monitoring points are typical of the locations where voltage measurement contacts and current transducers should be installed for monitoring and fault detection. Detection of an abnormality in the electrical system generally is treated by transfer to a redundant generator and if it fails, to the auxiliary generator. The abnormality has to be sufficient to trip a circuit breaker (hard fault) or trip a limit device. There are no methods on modern aircraft to detect small amounts of current

line-to-ground (soft fault) or to discern if the trip signal is valid (bad data). Present-day commercial aircraft have sufficient monitoring only on the primary (or high power) circuits. The extensive secondary circuits have only over-current protection.

Figure 1 is a one-line diagram of a Boeing 737 primary 3-phase electrical system. The port side of the dual system is energized through the normal position of transfer relay #1 (24-50-01). This diagram for the port side has about 17 busses and 15 wires. On this part there is a 115Vac, 400 Hz network, transformer-rectifiers, inverters, and rectification for the 28Vdc sub-system. This one-line diagram is representative of redundant, radial systems on other aircraft such as the Boeing 777 (Andrade and Tenning, 1992) (Tenning, 1992). The electrical system is basically a radial topology where only one source at a time, Generator #1, #2 or the APU supplies the system. Figure 1 does not show the AWG size or length of the power transmission lines, connectors, or wires bundled together in harnesses.

Consider generator #1 as supplying all power in normal operation. The generator feeds the network through breaker 1 to generator bus 1. From generator bus 1 there are 3 active lines, to main bus 1, to transfer bus 1, and to the battery charger via the

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ground service bus. Thus far, this is a 5 bus, 4 line, radial topology.

2 STATE ESTIMATION

State Estimation is a well-known power system monitoring algorithm which is extensively used on 3-phase earth power systems. It is almost a 'standard' program resident in large utilities energy management system computers (Kusic, 1985).

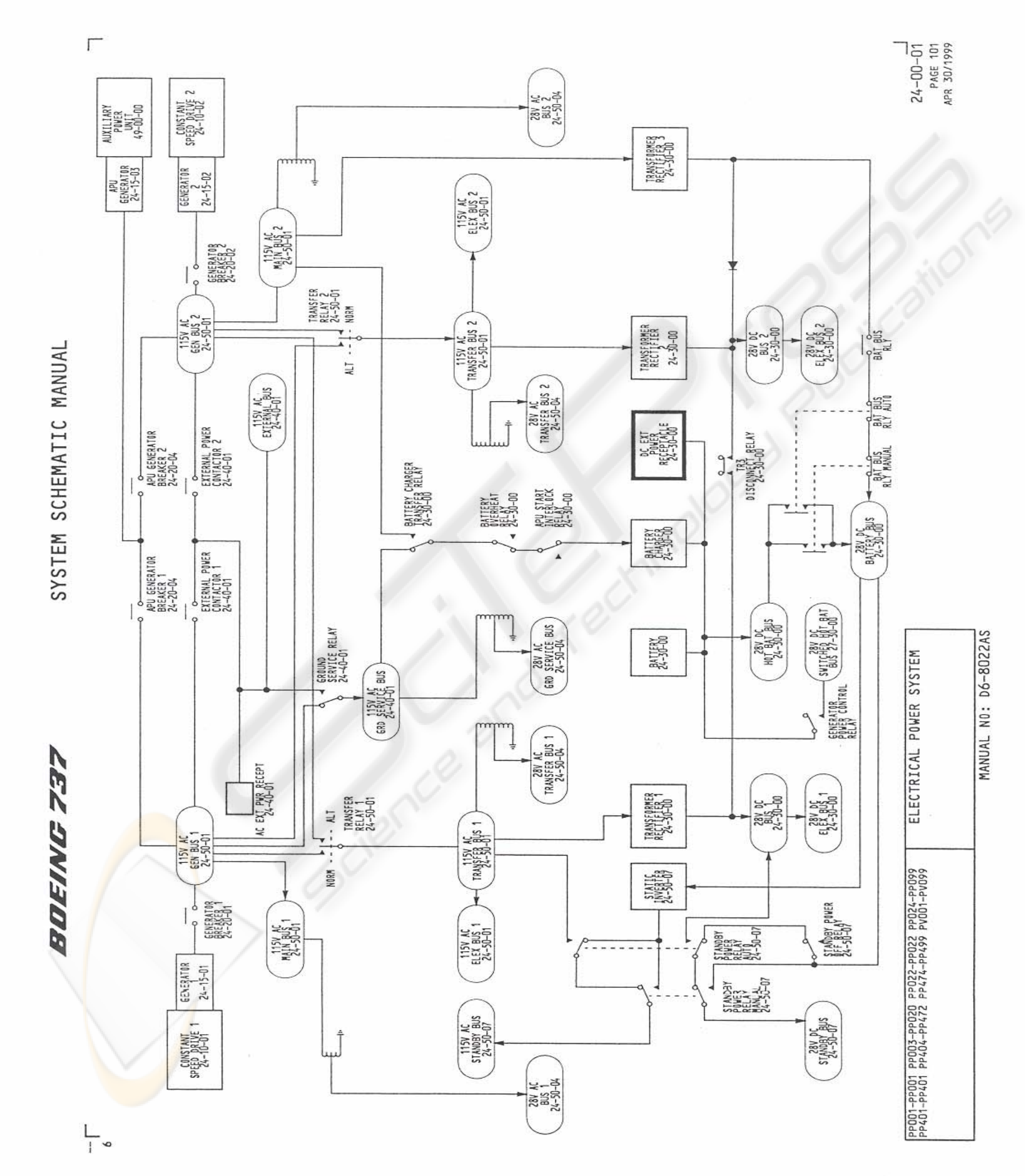

Figure 1: Boeing 737 Primary Electrical System

The network simulated by the State Estimation program consists of single phase pi equivalent models for balanced 3-phase transmission lines, and busses where power is injected or extracted from the network. Each bus of the electrical network has voltage, current, and injected power measurements at the bus with additional metering on transmission lines connected to the bus (node) as shown in Figure 2. Pi equivalent line parameters are used to describe a distributed line.

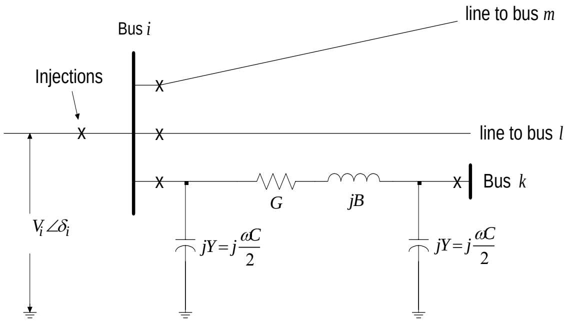

Figure 2: Connection of a Bus into a Network (Measurements shown by X's)

A dc network has only resistance, but the more general case is where each 400 Hz ac transmission line is modeled by the pi - equivalent where $G + jB = 1/(R + j\omega L)$ with R the line series resistance, L the line series inductance and $G + jB$ is the derived admittance. The line-to-neutral capacitance is C and ω represents the power frequency in radians per second. If a three-phase power scheme is used, then the pi network is the balanced flow single line equivalent. For the case of dc power, B and C are set to zero and there are no corresponding reactive power flow or phase angles.

The sensor signals are measured quantities from the real electrical network and indicated by X's of figure 2. These are measurements from the network as performed by current transformers, step-down potential transformers, inherent to equipment such as regulators, over-current protection, etc. For power flow on the line from bus i to bus k, near bus i the measurement would be positive in value while near bus k it is negative.

Each X on the network of figure 2 consists of up to 4 electrical quantities. The injection measurements at bus i are given in figure 3 where p.u. stands for per unit as defined on the power base. The bus injection measurements P_i and Q_i can be either positive or negative and often represent the power demand of lower voltage circuits or many lines connected to this point. The real and reactive power measurements describe the relative phase angle between the bus voltage and local current measurements

P_i	≡ Real power injected (Either watts or p.u.)
Q_i	≡ Reactive power injected (Either not-amperes – reactive, VARS, or p.u.)
$\lvert I_i \rvert$	≡ Absolute magnitude of the current (Either amperes or p.u.)
$\lvert V_i \rvert$	≡ Absolute magnitude of the line-to neutral voltage (Either volts or p.u.)

Figure 3: Bus Injection Measurements

Observe there is no phase angle measurement associated with voltage and current. The phase angle difference between bus i and bus k, which is necessary to describe line power flow, is not measured with present-day instrumentation on earth power systems. However, for compact aircraft systems, it may be possible to directly measure phase angles. Angle measurements would re-formulate the State Estimator.Injection and line flow measurements for the complete network are obtained from the transducers at an instant of time referred to as a 'snapshot'. 'Snapshot' is State Estimator terminology for simultaneous measurements performed by every transducer. If the network has slowly changing electrical power demand and the computer time for a scan of all digitally encoded data is fast enough, the 'snapshot' concept is valid. Experience on the U.S. 60 Hertz power transmission system has shown that thousands of lines and busses can be scanned fast enough by the data acquisition system to represents a 'snapshot' valid for the state estimation computation.

P_{ik}	≡ Real power flow from bus i towards bus k (Watts or p.u.)
Q_{ik}	≡ Reactive power flow from bus i towards bus k (Volt-Amperes- Reactive, VARS, or p.u.)
$\lvert I_{ik} \rvert$	≡ Absolute magnitude of the line current (Either amperes or p.u.)
$\lvert V_i \rvert$	≡ Line to neutral voltage at the bus (Volts or p.u.)

Figure 4: Line Flow Measurements

The measurements of a snapshot are the 'sensor' data for the State Estimator and fault detection. The weighted measurements from the power system such as a line power flow measurement near the i bus toward bus k, $S_{ik} = Z_{m1} + jZ_{m2}$ where the complex j term is for reactive power, are used in the performance index:

$$J = Sum\{W_i(h_i - Z_{mi})^2\} \qquad (1)$$

In equation 1, the h_i are calculated using the state of the power system. For example, real and reactive power flow on a transmission line connected from bus i to bus k are calculated as:

$$h_1 = P_{ik} = GV_i^2 - GV_iV_k\cos(\delta_i - \delta_k) - BV_iV_k\sin(\delta_i - \delta_k) \qquad (2A)$$

$$h_2 = Q_{ik} = -YV_i^2 - BV_i^2 - GV_iV_k\sin(\delta_i - \delta_k) + BV_iV_k\cos(\delta_i - \delta_k) \qquad (2B)$$

where *G*, *B*, and *Y* are parameters of the transmission line. Injections at a bus i are essentially a sum of all the flows on transmission lines connected to the bus.

The J performance index of equation 1 is minimized by up-dating the state vector x at each iteration by means of increments calculated in the Newton-Raphson expression:

$$\Delta x = \Delta\begin{vmatrix} V \\ \delta \end{vmatrix} = -\left|\frac{\partial^2 J}{\partial x^2}\right|^{-1}\frac{\partial J}{\partial x} \approx -\left[\frac{\partial \bar{h}^t}{\partial x}W\frac{\partial \bar{h}}{\partial x}\right]^{-1}\frac{\partial J}{\partial x}$$

(3)

where only the vector $x = [V \ \ \delta]^t$ appears in the Jacobian approximation and second-order effects in the Jacobian are ignored. The partial derivatives of h are derived from analytical expressions for line flows, currents, etc, similar to equations 2A and 2B. For example, partial derivative of equations 2A and 2B exist with respect to variables V_i , V_k, δ_i, and δ_k.

Let H = $\delta h/\delta x$ be the linearized gradient evaluated at the final value of the state vector, x. H is used to compute the covariance matrix for the measurements:

$$\Sigma^2 = W^{-1} - H\,[H^t\, W\, H]^{-1}\, H^t \qquad (4)$$

From this matrix, Σ_i is the standard deviation of measurement i and is the square root of the i^{th} diagonal. When the standard deviation is used to normalize the residual value

$$\tau = |h(X)_i - Z_{mi}|/\Sigma_i$$

(5)

for each measurement, it has been proven that the largest among all normalized residuals is the most probable bad data (Broussolle, 1978). Thus voltages, currents, etc. are compared on the same basis to find the bad data. This is a salient feature of State Estimation—to detect bad measurement data from transducers.

With no faults on the network, the residual standard deviation values calculated by equation 5 are due to errors in the 'true' or physical line parameters compared to the values used in the computation. Also the parasitic errors in the transducers such as accuracy, linearity, and D/A round-off are part of the residual. A 'bad' data measurement must exceed several multiples of the residual value to be considered invalid and avoid false alarms.

Assume that sensor data is valid and that a high impedance line-to-line fault is present on the network. The fault impedance (resistive only) is sufficiently high so as to not trip the protective circuit breakers at the ends of the line, but it is sufficient to be detected by accuracy checks on measurements and cause 'bad data' at both ends of the line. The location of the fault is one the line with 'bad' data on both ends. A series fault such as occurs due to contacts separating, corrosion of the contact, or wire strands broken, is found by propagating through the network the differences between calculated sensor values and measurements.

The time interval to scan all the network transducers is considered to be very small compared to the time duration of electrical load/generation changes on the network. Thus the 'snapshot' of data used in the State Estimator is a steady-state operating condition. This same time approximation may be extended to future variable frequency systems, where the frequency at the start of the snapshot is sufficiently close to the frequency at the end of the snapshot, such that a steady-state exists.

These fault detection methods based upon State Estimation have been demonstrated on 6 terrestrial power systems with 3-phase transmission lines between 118 kV and 565 kV. They have also been applied to the first aircraft electrical system, the Wright-Patterson Air Force 270 Vdc MADMEL test bed (Maldonado et al., 1997) (Kusic, 2000), which is representative of an F-18 aircraft. The MADMEL tests indicate the derivation for 3-phase ac systems is valid for the special case of direct current systems. For dc systems, there is no reactive power flow, no line inductance or line charging, and the state consists of the voltages at the busses.

3 A 270 Vdc NETWORK

Main power lines on aircraft are large gage wire, or for flexibility consist of parallel smaller gage wires, both of which have on the order of several milliohms resistance. Figure 5 shows a radial topology 5 bus (diamonds) network with resistances on the same order of magnitude of the primary circuit of the 270 Vdc MADMEL electrical test bed. The network of figure 5 is used to demonstrate State Estimation (for the dc special case) and fault detection methods.

Because resistances are very low in the network of figure 5, the voltage drops when current is being conducted are on the order of tenths of volts, which is often less than the 0.5% or 1% accuracy of ground to bus voltage measurement transducers. Such small voltage drops were accurately measured (Kusic, 2000) in the Wright-Patterson Air Force Base MADMEL test bed for the F-18 by means of a differential voltage scheme using the 270Vdc as a reference as shown in figure 6. This MADMEL instrumentation was duplicated to obtain measurements on the network of figure 5.

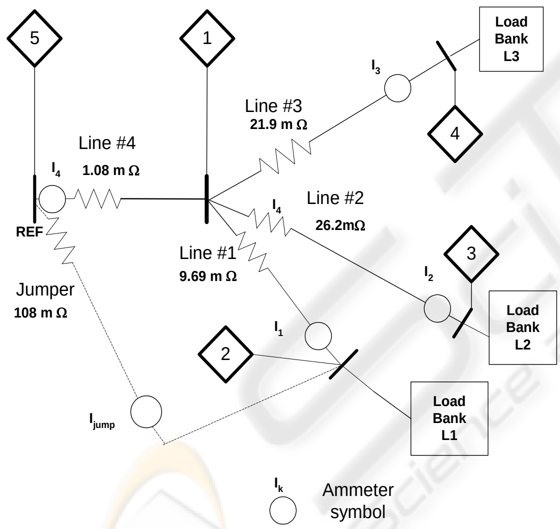

Figure 5: Experimental Test Topology (The jumper is for calibration only.)

A photograph of the line structure and ammeters in a laboratory experiment setup is shown in figure 7. The resistance of an ammeter is incorporated into the line resistances specified on figure 6. Line #4 from the 270Vdc reference to bus 1 is constructed of calibrated dc current shunts, but the equivalent resistance is also affected by the contacts.

The jumper wire shown in figure 6 is not a normal part of the radial network. The jumper was sequentially connected to bus 2, then 3, then 4 to estimate the resistance of the transmission lines. Line parameters B, G, Y are determined from the gradient and Jacobian in a Newton-Raphson computation:

$$p = \begin{vmatrix} B \\ G \\ Y \end{vmatrix} = -\left|\frac{\partial^2 J}{\partial p^2}\right|^{-1} \frac{\partial J}{\partial p} = -\left[\frac{\partial \bar{h}^t}{\partial p} W \frac{\partial \bar{h}}{\partial p}\right]^{-1} \frac{\partial J}{\partial p}$$

(6)

The loop is opened then the unused measurements are then used to determine line parameters. This method applies if the line is in a loop. For a radial network, a "jumper" must be added to "calibrate" the network. The jumper is removed for normal operation.

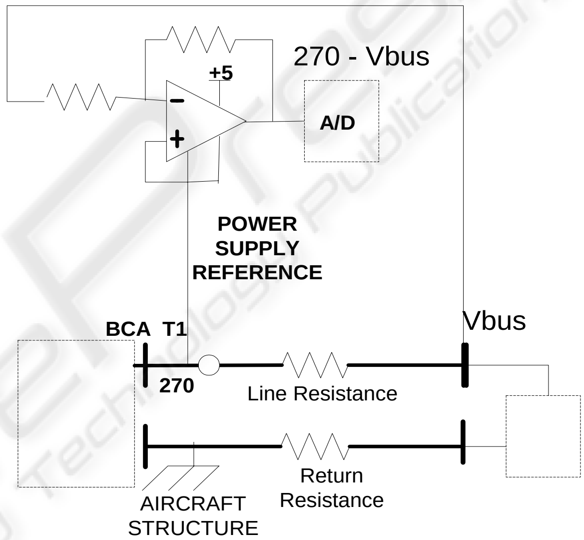

Figure 6: Method of Differential Voltage Measurement Used on the Test Bed of Figure 6

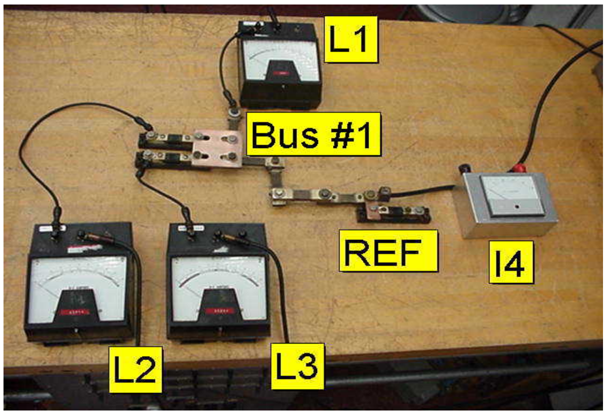

Figure 7: Current Metering on the 270 Vdc Laboratory Network (Ammeters are in lines #1, #2, and #3 connected to resistive load banks L1, L2, and L3 respectively)

The State Estimator uses a 'snapshot' of transmission line flow measurements and bus measurements to compute the state of the network. For the dc network of figure 6 the state is the voltages at all the busses, V = [V1, V2, V3, …..] and the 'snapshot' consists of voltage and current measurements performed on the network with bus #5 set to 270 Vdc:

Z_{meas} = [V_{1meas}, V_{2meas}, V_{3meas}, V_{4meas}, …, $I_{1,2meas}$, $I_{1,3meas}$, $I_{2,3meas}$, $I_{3,2meas}$, ….] (7)

In equation 7 the $I_{j,k\ meas}$ are measured line currents at bus j towards bus k. If no errors are present in the data snapshot, the state agrees exactly with the state computed by a power flow calculation (Kusic, 1985). An important principle is the State Estimation method uses one bus as the 'slack' or reference bus on the system, and all other bus voltages are computed as differences of voltages between it and the slack bus. For equation 6, bus #5 is at 270 Vdc. The slack bus principle is the reason the differential scheme of figure 7 was effective.

The complete snapshot of data with a jumper connected between the reference bus and bus #2 of the network is as follows:

Z_{meas} = [V_{1meas}, V_{2meas}, V_{3meas}, V_{4meas}, …,
$I_{1,2meas}$, $I_{1,3meas}$, $I_{1,4meas}$, $I_{1,5meas}$, I_{jump}.]
=[269.98517, 269.94738, 269.88851, 269.93169, 4.2, 3.8, 3.95, -11.95, 0.65] (8)

When the measurement vector of equation 8 was used in the parameter estimation program (equation 6), it resulted in the resistance of transmission line #1 to be: Transmission line #1 = 12.56 milliohms

This was the only transmission line that could be estimated with the data of equation 8 before accumulated measurement errors resulted in impossible parameter estimation for other lines, or repeatedly returned transmission line #1 to be estimated. Observe that transmission line #1 was originally taken as 9.69 milliohms.

Using the same steps that resulted in the measurement vector equation 8, two other jumper connections were used to create loops for parameter estimation. These were obtained with a source voltage of Vdc = 260, and resulted in the estimated parameters shown in figure 9.

Transmission Line	Initial Resistance	Estimated Resistance
#1	9.69 milliohms	12.56 milliohms
#2	26.2 milliohms	24.85 milliohms
#3	21.9 milliohms	-----
#4	1.08 milliohms	----
Jumper	108 milliohms	100.93 milliohms

Figure 8: Summary of Transmission Line Estimates for the Experimental Network of Figure 6

4 BASE CASE

The transmission line parameters of the experimental network have been estimated (figure 8) in the previous section. The network is considered un-faulted. A 'snapshot' is taken of the radial network operating at nominal loads, without jumpers, in order to obtain residual values of bad data and residual errors for fault detection. Residual errors are due to inherent inaccuracies in measurements, transmission line parameters, and temperature changes. A 'snapshot' is taken on the radial network with nominal loads on at busses #2 to #4. The measured bus voltages and currents I_1 to I_4, with the reference bus #5 operated at 257Vdc are:

Z_{meas} = [256.97510, 256.92351, 256.87323, 256.75924, 4.87, 3.85, 10.0, -18.6] (10)

The State Estimator results for this operating condition using the estimated transmission line parameters are presented in figure 10. Figure 10 shows calculated values of P,Q,I,V as estimated from the snapshot of equation 10. All normalized residual errors, equation 5, are less than 5 X 10^{-5}

Number of measurements + parameters = 44
Pbase = 27000 Vbase = 270 stest = 0.0030
********* BUS SUMMARY*********************

	meas	NORM. ERR.
1 BUS 1	0.9518	0.0000
2 LOAD_L1	0.9516	0.0000
3 LOAD_L2	0.9514	0.0000
4 LOAD_L3	0.9510	0.0000
5 REF BUS	0.9519	0.0000

*********** LINE FLOW SUMMARY*********

Bus 1 V= 0.952 p.u.

FROM	TO	MEASURE		NORM ERROR
BUS #1	LOAD_L1	P,pu	0.0464	0.0000
BUS #1	LOAD_L1	I,pu	0.0487	0.0000
BUS #1	LOAD_L1	Q,pu	0.0000	0.0000
BUS #1	LOAD_L1	V,pu	0.9518	0.0000
BUS #1	LOAD_L2	P,pu	0.0366	0.0000
BUS #1	LOAD_L2	I,pu	0.0385	0.0000
BUS #1	LOAD_L2	Q,pu	0.0000	0.0000
BUS #1	LOAD_L2	V,pu	0.9518	0.0000
BUS #1	LOAD_L3	P,pu	0.0952	0.0000
BUS #1	LOAD_L3	I,pu	0.1000	0.0000
BUS #1	LOAD_L3	Q,pu	0.0000	0.0000
BUS #1	LOAD_L3	V,pu	0.9518	0.0000
BUS #1	REF BUS	P,pu	-0.1770	0.0000
BUS #1	REF BUS	I,pu	-0.1860	0.0000
BUS #1	REF BUS	Q,pu	-0.0000	0.0000
BUS #1	REF BUS	V,pu	0.9518	0.0000

Bus 2 LOAD_L1 V= 0.952 p.u.

		MEASURE		NORM ERROR
LOAD_L1	BUS #1	P,pu	-0.0463	0.0000
LOAD_L1	BUS #1	I,pu	-0.0487	0.0000
LOAD_L1	BUS #1	Q,pu	-0.0000	0.0000
LOAD_L1	BUS #1	V,pu	0.9516	0.0000

Bus 3 LOAD_L2 V= 0.951 p.u.

		MEASURE		NORM ERROR
LOAD_L2	BUS #1	P,pu	-0.0366	0.0000
LOAD_L2	BUS #1	I,pu	-0.0385	0.0000
LOAD_L2	BUS #1	Q,pu	-0.0000	0.0000
LOAD_L2	BUS #1	V,pu	0.9514	0.0000

Bus 4 LOAD_L3 V= 0.951 p.u.

		MEASURE		NORM ERROR
LOAD_L3	BUS #1	P,pu	-0.0951	0.0000
LOAD_L3	BUS #1	I,pu	-0.1000	0.0000
LOAD_L3	BUS #1	Q,pu	-0.0000	0.0000
LOAD_L3	BUS #1	V,pu	0.9510	0.0000

BUS 5 REF BUS V= 0.952 p.u.

		MEASURE		NORM ERROR
REF BUS	BUS #1	P,pu	0.1770	0.0000
REF BUS	BUS #1	I,pu	0.1860	0.0000
REF BUS	BUS #1	Q,pu	0.0000	0.0000
REF BUS	BUS #1	V,pu	0.9519	0.0000

Figure 9: State Estimator Results for Experimental Test Bed (No Faults)

In figure 9 note the voltage base is 270 Vdc, so the reference bus is operating at 257/270 = .951851851 per unit. The base current is 100 Amperes, such that current in line #1 is 4.87 Amperes or .0487 per unit. The real power is computed as measured voltage times measured current. Observe that the reactive power is carried through the computation, but is always zero.

An examination of the normalized residual errors in figure 9 (not shown here), indicates the largest value is 4.1 $X10^{-5}$ for the voltage mismatch on line #2 due to current flow from bus #3 to bus #1. The criterion for bad data is set to **stest** = $3X10^{-3}$ which is many orders of magnitude higher than 4.1 $X10^{-5}$. When a normalized residual is above **stest** in value, it is considered to be 'bad data'.

The base case represents the aircraft electrical system 'as built', or in other words, the original un-faulted condition. The resistance of the wires in the harnesses plus connectors plus transfer relays are all included in the line resistance (e.g., figure 8).

5 SERIES FAULT DETECTION

Consider that the aircraft has aged over a period of years and either corrosive effects or handling and bending of connecters or lines has increased the resistance of a line. The as-built values of the transmission lines are the estimated parameters of figure 8. However, transmission line #1 has an increase of 0.5 milliohms resistance increase due to a series fault. This fault was experimentally set up by inserting a 0.5 milliohm calibrated resistance into transmission line #1 and taking a snapshot of operation with the additional resistance. The snapshot of data is:

$$Z_{meas} = [V_{1meas}, V_{2meas}, V_{3meas}, V_{4meas}, \ldots, I_{1,2meas}, I_{1,3meas}, I_{1,4meas}, I_{1,5meas}] = [265.978, 265.972, 265.887, 265.832, 7.05, 3.92, 8.05, -18.8] \quad (11)$$

This snapshot is a different operating condition from the base case, but operating with the fault. The State Estimator results with this snapshot are in figure 10.

Number of measurements + parameters, = 44
Pbase = 27000 Vbase = 270 stest = 0.0030
************ **BUS SUMMARY** ************

BUS	VOLTAGE (pu) meas	NORM. ERR.
BUS 1	0.9851	0.0000
LOAD_L1	0.9848	0.0000
LOAD_L2	0.9847	0.0000
LOAD_L3	0.9845	0.0000
REF BUS	0.9852	0.0000

*************LINE FLOW SUMMARY **********

FROM	TO	(pU)		
BUS 1	**BUS #1**	**V= 0.985 p.u.**		
		MEASURE	NORM	ERROR
BUS #1	LOAD_L1	P,pu	0.0694	0.0000
BUS #1	LOAD_L1	I,pu	0.0705	0.0000
BUS #1	LOAD_L1	Q,pu	0.0000	0.0000
BUS #1	LOAD_L1	V,pu	0.9851	0.0000
BUS #1	LOAD_L2	P,pu	0.0386	0.0000
BUS #1	LOAD_L2	I,pu	0.0392	0.0000
BUS #1	LOAD_L2	Q,pu	0.0000	0.0000
BUS #1	LOAD_L2	V,pu	0.9851	0.0000
BUS #1	LOAD_L3	P,pu	0.0793	0.0000
BUS #1	LOAD_L3	I,pu	0.0805	0.0000
BUS #1	LOAD_L3	Q,pu	0.0000	0.0000
BUS #1	LOAD_L3	V,pu	0.9851	0.0000
BUS #1	REF BUS	P,pu	-0.1852	0.0001
BUS #1	REF BUS	I,pu	-0.1880	0.0001
BUS #1	REF BUS	Q,pu	-0.0000	0.0000
BUS #1	REF BUS	V,pu	0.9851	0.0000
BUS 2	**LOAD_L1**	**V= 0.985 p.u.**		
		MEASURE	NORM	ERROR
LOAD_L1	BUS #1	P,pu	-0.0694	0.0000
LOAD_L1	BUS #1	I,pu	-0.0705	0.0000
LOAD_L1	BUS #1	Q,pu	-0.0000	0.0000
LOAD_L1	BUS #1	V,pu	0.9844	0.0004
BUS 3	**LOAD_L2**	**V= 0.985 p.u.**		
		MEASURE	NORM	ERROR
LOAD_L2	BUS #1	P,pu	-0.0386	0.0000
LOAD_L2	BUS #1	I,pu	-0.0392	0.0000
LOAD_L2	BUS #1	Q,pu	-0.0000	0.0000
LOAD_L2	BUS #1	V,pu	0.9848	0.0000
BUS 4	**LOAD_L3**	**V= 0.984 p.u.**		
		MEASURE	NORM	ERROR
LOAD_L3	BUS #1	P,pu	-0.0793	0.0000
LOAD_L3	BUS #1	I,pu	-0.0805	0.0000
LOAD_L3	BUS #1	Q,pu	-0.0000	0.0000
LOAD_L3	BUS #1	V,pu	0.9846	0.0001
BUS 5	**REF BUS**	**V= 0.985 p.u.**		
		MEASURE	NORM	ERROR
REF BUS	BUS #1	P,pu	0.1852	0.0001
REF BUS	BUS #1	I,pu	0.1880	0.0001
REF BUS	BUS #1	Q,pu	0.0000	0.0000
REF BUS	BUS #1	V,pu	0.9852	0.0000

Figure 10: State Estimator Results for 0.5 milliohm Series Fault in Line #1

The normalized voltage error in transmission #1 at LOAD #1 has a value 4 X 10^{-4} so line #1 is identified as the 'faulted' transmission line because it has a much higher residual than the criterion of 4.1 $X10^{-5}$ of normal operation. When the fault magnitude is increased to 5.0 milliohms, the normalized voltage error at LOAD #1 increases to 4.8 $X10^{-4}$, so the detection is relatively insensitive to the magnitude of the fault.

The line where the fault is located, so long as normalized error is above the minimum level, or a threshold set from the base case (no fault condition). To treat the case of multiple normalized errors above the minimum level, the errors are weighted and propagated through the network to find the largest weighted error. This largest weighted error always corresponds to the faulted line. The line with the fault is always detected.

This fault example has considered all data in the 'snapshot', equation 11, to be valid. 'Bad data' errors could originate in electronic equipment failures in the voltage transducers, current transducers, A/D converters, data acquisition, memory, and other sources. For example, the valid voltage measurement at bus #2 is 265.972. If this voltage value is changed to 264.972 or 266.972, then the normalized residual increases to 4.1 $X10^{-3}$ and 3.3 $X10^{-3}$ respectively. It is necessary to eliminate the 'bad data' before series fault detection.

6 OTHER FAULTS

Bus faults are detected as bad data for zero injection values at the bus. For example, if all the transmission line power flows from a bus are measured the sum is zero, therefore $P_i = 0$, $Q_i = 0$, $|I_i| = 0$ for the injections. When the normalized residual of these injections is the largest of residuals, the bus has faulted.

Transmission line to ground faults are detected by means of the residuals at the ends of the line. If the residuals for real power flow (ac or dc systems) or current (dc system only) are above the threshold for bad data, then the line has a shunt fault to ground.

7 CONCLUDING REMARKS

The dc example is a special case of the 3-phase ac case where the line flows and the fault is balanced. To detect a single phase fault on a 3-phase system, each phase must be instrumented and the State Estimator algorithm must be extended to single phase with mutual coupling. The added weight for single phase transducer measurements may be prohibitive.

State Estimation power flow depends on small voltage differences, and small phase angle differences for the ac case, such that differential voltage measuring methods should be used.

Tolerances of 1% accuracy for line-to-line transducers cannot be used for fault detection, because the measurement errors exceed the small voltage differences from bus-to-bus.

For dc aircraft systems the weight of the transducers, when applied to only the high power primary part, is acceptable for improved monitoring. The International Space Station accepted the weight penalty in order to employ State Estimation on its 150 Vdc primary system (Kusic, 1989). An extension for fault detection requires voltage difference measurements or a reference distributed to each measurement point. Military aircraft use proportionately more electronics than commercial aircraft. For dc systems, the dc/dc conversion is advantageous over ac/dc conversion, so instrumentation is available for the fault detection methods. Future aircraft may employ more electrical power equipment (Briere. et.al., 1995) where monitoring and fault detection are even more necessary.

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