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STATE ESTIMATION WITH PHASOR MEASUREMENTS

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ABSTRACT

The recent introduction of microprocessors into substations for protection and control makes it possible to measure positive sequence voltage phasors and positive sequence transmission line current phasors in real time. It is necessary to synchronize sampling clocks in various substations in order to put the phasors on a common reference. Techniques for synchronizing sampling along with a method for obtaining positive sequence phasors from samples are reviewed. Although it is possible to use these direct measurements in conventional state estimation algorithms, considerable advantage accrues if the state estimation is reformulated in terms of direct measurements of phasor voltages and currents. The resulting estimation algorithm involves an admittance like matrix with the sparsity of the admittance matrix. The new matrix is real rather than complex even for small X/R ratios for the lines. The algorithm requires no assumptions as to decoupling, flat voltage profiles, small resistance, etc. The algorithm converges in one step with the same amount of computation as one iteration of existing estimators. Examples are given for the IEEE 118 bus system.

INTRODUCTION

Most modern Power System Control Centers use Static State Estimation as a basis for on-line security monitoring functions. The theory of Power System State Estimation evolved over a decade - in the mid-sixties to seventies - and although work continues on enhancing the state estimators currently in use, the basic structure of state estimator algorithms has remained unchanged. The measurement set consists of complex power flows, voltage magnitudes, complex power injections at some buses, etc. which are non-linear functions of the system state. The non-linear equations are linearized and an iterative Weighted Least Square estimator applied to the measurement set. [1,2,3] Real-time complex power and voltage magnitude measurements are obtained throughout the system by scanning, and the new measurements are used to update the state estimate with the previous estimate as the starting point. With careful programming and with normal system conditions the new state can be obtained in just a few iterations.

In recent years a significant new development has taken place in the field of computer based relaying - a field somewhat removed from power system operations and control. Yet the developments in computer relaying are likely to have a far-reaching influence on the monitoring, operation, and control of power systems. [4,5] This paper will consider one such influence: the direct measurement of phasor by computer relays and their use in static state estimation.

A computer based transmission line relay has been developed (and is undergoing field tests at the present time) which has particularly advantageous features in this respect. The Symmetrical Component Distance Relay (SCDR) [6,7,8] has a front-end processing algorithm which calculates symmetrical components of the transmission line voltages and currents in real time from their sampled data. These calculations produce very accurate phasor measurements which can also be used to calculate the local system frequency with very high resolution. [8] As the computer based relays are a part of the substation computer hierarchy - which in turn can be a part of a system wide computer hierarchy - these real time phasor measurements can be communicated to a system control center in real-time. It is well to recall that the system model used in all state estimation algorithms is the positive sequence network representation, consequently the positive sequence measurements of voltages and currents are the appropriate quantities for state estimation purposes. In particular these measurements are superior to other proposed schemes which are based on measurements carried out on one phase of the system along with the zero crossing of its waveform being used for phasor angle measurements. [9,10] The technique used in the SCDR is based upon the Discrete Fourier Transform calculation from sampled data and is therefore free from errors introduced by system unbalances and harmonics.

The paper begins with a brief review of the symmetrical component measurement technique used by the SCDR. To obtain all phasor measurements with a common reference, it is necessary to synchronize the sampling clocks at all the substations within the monitored system. Some alternatives for clock synchronization are discussed next. This is followed by the theory of state estimation with voltage and current phasors as system measurememts. The features of this procedure are contrasted with state estimators using power flow measurements. The new state estimator performance has been verified through Monte Carlo simulations on the IEEE 118 bus system. These results are presented, along with a discussion of the special case where the measurement set consists of only the positive sequence voltage phasors. Finally, the prospects for using the technique presented here in other environments, along with some initial plans for experimental verification of these concepts are discussed in the Conclusions section of the paper.

SYMMETRICAL COMPONENTS FROM SAMPLED DATA

This review refers to voltages at a line terminal, although identical relations hold for line currents as well. Assume that the three phase-to-neutral voltages are filtered through appropriate anti-aliasing filters and sampled at a sampling rate of 720 Hz (12 times the

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nominal power frequency). The samples for one period of the fundamental frequency are $(v_{ak}, v_{bk}, v_{ck},\ k=1,2,\ldots,12)$. Then the (fundamental frequency) positive sequence voltage phasor is given by

$$V_1 = V_{1r} + V_{1i} \qquad (1)$$

where

$$V_{1r} = \frac{1}{18\sqrt{2}} \sum_{k=1}^{12} [v_{ak} \sin k.30° + v_{bk} \sin (k-4).30° + v_{ck} \sin (k+4).30°]$$

and

$$V_{1i} = \frac{1}{18\sqrt{2}} \sum_{k=1}^{12} [v_{ak} \cos k.30° + v_{bk} \cos (k-4).30° + v_{ck} \cos (k+4).30°] \qquad (2)$$

These equations (as well as those for negative and zero-sequence quantities) are computed recursively by the front-end program of the SCDR. The reference of the phasor in equation (1) is determined by the instant at which the first sample (k=1) is taken. Assuming that these sampling instants are synchronized at all buses, positive sequence voltage phasor measurements on a common reference would result. [7] Note also that in case of harmonic distortions of the voltage waveforms, the calculations given by equations (1) and (2) represent a digital filter which produces a pure fundamental frequency component. Although the above procedure has been formulated in terms of one period of the waveform, longer or shorter duration algorithms are available. [11] The errors in the phasor estimate are inversely proportional to the data window used in these calculations. Depending upon the scan rate to be used in collecting the positive sequence voltage measurements, longer data windows could be used.

SYNCHRONIZATION OF SAMPLING CLOCKS

As mentioned previously, the sampling clocks used to measure various phasors at different substations must be synchronized in order to have a common frame of reference. If clocks are synchronized to within about 10 microseconds, the phase angles of the phasors will be within about 0.2 degree of their correct value on a 60 Hz basis. Presently available inexpensive receivers of WWVB signals can provide coincidence of sampling pulses to within about 100 to 1000 microseconds. These receivers are thus about one or two orders of magnitude too coarse for the present need. More expensive LORAN-C receivers with accuracies of a microsecond are also currently available. Another alternative would be to use a dedicated synchronizing medium - such as microwave or fiber-optic links between substations. Clearly such channels can not be installed economically for the purpose of clock synchronization, but once in place for other reasons they become a very attractive option for this purpose. Schemes of this type are reported to be in use in Japan [12] in a digital relaying scheme.

STATE ESTIMATION WITH PHASOR MEASUREMENTS

It will be assumed that real time measurements of all positive sequence bus voltages and some positive sequence currents in transmission lines and transformers are available as input to the state estimator. Each measurement is assumed to have a noise component ε. The measurement vector M is given by

$$M = \begin{bmatrix} E_B \\ \\ I_L \end{bmatrix} + \begin{bmatrix} \varepsilon_B \\ \\ \varepsilon_L \end{bmatrix} \qquad (3)$$

where E_B and I_L are vectors of true values of the measured bus voltages and element currents, and ε_B and ε_L are the noise vectors corresponding to the voltage and current measurements.

Consider an entry I_{pq} of the vector I_L corresponding to the true current at the p terminal of an element connecting buses p and q (see Figure 1). y_{pq},

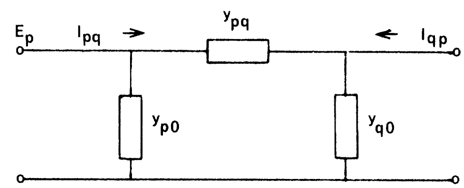

Figure 1
Transmission Line admittances, voltages, and currents

y_{p0} and y_{q0} are the series and shunt admittances of the element pq. It follows from Figure 1 that

$$I_{pq} = y_{pq} (E_p - E_q) + y_{p0} E_p \qquad (4)$$

If A is the current measurement-bus incidence matrix (defined in a manner analogous to the element-bus incidence matrix [13]), it follows that

$$I_L = [y A^t + y_s] E_B \qquad (5)$$

where y is the diagonal primitive matrix of all series admittances of the metered elements, and y_s is the primitive matrix of all the shunt admittances at the metered ends. If the total number of buses (excluding the reference) in the system is <u>b</u>, the total number of elements is <u>e</u>, and total number of current measurements is <u>m</u>, then y is mxm and diagonal, A is mxb and y_s is mxb. If each terminal of all the elements is metered, m = 2e. However, it is expected that m << 2e as not all element currents would be measured.

The covariance of the errors is given by

$$E\{\varepsilon.\varepsilon^t\} = W = \begin{bmatrix} W_B & 0 \\ 0 & W_L \end{bmatrix} \qquad (6)$$

and the noise is assumed to have zero mean. If the measurements are un-correlated, W_B and W_L are diagonal matrices.

Substituting equation (5) into (3)

$$M = \begin{bmatrix} \mathbf{1} \\ \hline y\ A^t + y_s \end{bmatrix} E_B + \begin{bmatrix} \varepsilon_B \\ \hline \varepsilon_L \end{bmatrix} \qquad (7)$$

$$= B.E_B + \varepsilon \qquad (8)$$

where B is the coefficient matrix of E_B in equation (7).

The Weighted Least Square estimate for E_B is given by (superscript † standing for complex conjugate transpose of a matrix)

$$B^{\dagger}.W.B\ E_B = B^{\dagger}.W.M \tag{9}$$

or

$$G.E_B = B^{\dagger}.W.M \tag{10}$$

where G, the gain matrix is given by

$$G = B^{\dagger}.W.B \tag{11}$$

The state estimator algorithm consists of computing $B^{\dagger}.W.M$ for each measurement scan, and then solving equation (10) for the state vector E_B. The gain matrix G is constant, and LU factors of G are computed once and saved for later use. Note that the solution is direct: no iterations are involved. The LU factors of G can be used as long as the system configuration remains unchanged and measurement errors remain same.

STRUCTURE OF THE GAIN MATRIX G

The nature of the gain matrix can be better understood if it is expressed in terms of its partitions:

$$\begin{aligned} G &= B^{\dagger}.W.B \\ &= [\ \mathbb{1} \mid A\, y^{*} + y_s\ ] \begin{bmatrix} W_B & 0 \\ 0 & W_L \end{bmatrix} \begin{bmatrix} \mathbb{1} \\ y\, A^t + y_s \end{bmatrix} \\ &= W_B + y_s^{\dagger} W_L y_s + A\, y^{*} W_L\, y\, A^t \\ &\quad + (y_s^{\dagger} W_L y\, A^t) + (y_s^{\dagger} W_L y\, A^t)^{\dagger} \\ &= F + (H + H^{\dagger}) \end{aligned} \tag{12}$$

where

$$F = W_B + A\, y^{*} W_L y\, A^t + y_s^{\dagger} W_L y_s \tag{13}$$

and

$$H = y_s^{\dagger} W_L y\, A^t \tag{14}$$

The matrix F consists of W_B, the covariance of the bus voltage phasor measurements, the matrix $Ay^{*}W_L yA^t$ is a matrix like an admittance matrix, except that its entries are all real. For example, if the line connecting buses p and q has a series admittance of y_{pq}, the admittance-like term corresponding to this element would be $w_{pL}|y_{pq}|^2$ if a measrement corresponding to the p terminal of this line is included in the measurement set. The remaining part of F is $y_s\, W_L y_s$ which contains diagonal entries of $w_{pL}|y_{p0}|^2$ corresponding to the bus p measurement. Thus the matrix F can be viewed as the admittance matrix of a resistive network shown in Figure 2(a) if no current is measured at either terminal of the line, as shown in Figure 2(b) if current is measured at the p terminal, and as shown in Figure 2(c) if current is measured at both terminals. In all cases F is sparse, real, and symmetric regardless of the X/R ratios of the elements.

Now examine matrix H given by equation (14). If current at terminal p of line connecting buses p and q is measured, it can be seen by direct calculation that

$$H_{pp} = y_{p0}^{*} w_{pL}\, y_{pq} \tag{15}$$

$$H_{pq} = -\, y_{p0}^{*} w_{pL}\, y_{pq} \tag{16}$$

Similarly, if the q terminal current is also measured

$$H_{qp} = -\, y_{q0}^{*} w_{qL}\, y_{pq} \tag{17}$$

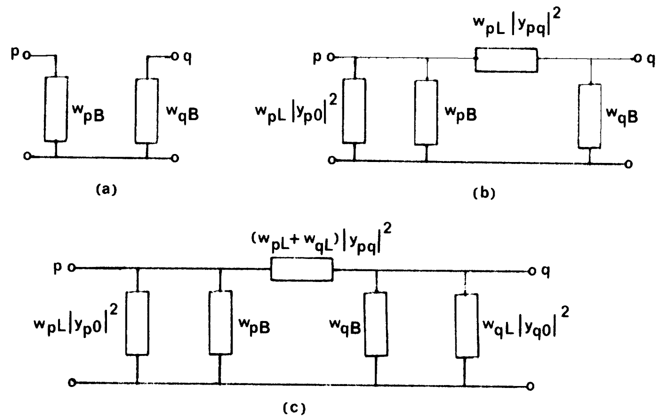

Figure 2

Conductances of Network represented by F. 2(a): No current measurement. 2(b): Current measurement at terminal p. 2(c): Current measurements at terminals p and q.

$$H_{qq} = y_{q0}^{*} w_{qL}\, y_{pq} \tag{18}$$

Thus

$$(H + H^{\dagger})_{pp} = 2\ \mathrm{Re}\ \{y_{p0}^{*} w_{pL}\, y_{pq}\} \tag{19}$$

$$(H + H^{\dagger})_{pq} = -\, y_{p0}^{*} w_{pL}\, y_{pq} - y_{q0}\, w_{qL}\, y_{pq}^{*} \tag{20}$$

$$(H + H^{\dagger})_{qp} = -\, y_{p0}\, w_{pL}\, y_{pq}^{*} - y_{q0}^{*} w_{qL}\, y_{pq} \tag{21}$$

$$(H + H^{\dagger})_{qq} = 2\ \mathrm{Re}\ \{y_{p0}^{*} w_{pL}\, y_{pq}\} \tag{22}$$

If the element in question is a transmission line with $y_{p0} = y_{q0}$ and the variance of the two current measurements is the same, then $(H + H^{\dagger})$ is a real symmetric matrix with a bus admittance matrix-like structure. If the element is a transformer with off-nominal turns' ratio, then all element admittances are imaginary, H is real but not symmetric, while $(H + H^{\dagger})$ is once again real and symmetric.

In case only one terminal - say terminal p - of element pq is measured, then

$$(H + H^{\dagger})_{pp} = 2\ \mathrm{Re}\ \{y_{p0}^{*} w_{pL}\, y_{pq}\}$$

$$(H + H^{\dagger})_{pq} = -\, y_{p0}^{*} w_{pL}\, y_{pq}$$

$$(H + H^{\dagger})_{qp} = -\, y_{p0}\, w_{pL}\, y_{pq}^{*}$$

$$(H + H^{\dagger})_{qq} = 0$$

The matrix $(H + H^{\dagger})$ is thus complex with rather small imaginary parts if X/R ratios of the lines are large.

The above discussion of the gain matrix can be summarized as follows:

(i) The gain matrix G is always a constant.

(ii) If voltage phasors alone are measured at all buses, the gain matrix is the covariance matrix of the measurements.

(iii) Where current phasors are measured, if they are measured at both ends of an element, the gain matrix is real and symmetric. It is also real and symmetric for transformers with off-nominal turns' ratios.

(iv) If some element currents are measured at one terminal only, the gain matrix has some complex off-diagonal entries. These entries have small imaginary parts for normal X/R ratios of lines.

SIMULATION RESULTS

The algorithm of equations (10) and (11) was programmed for the IEEE 118 bus system, and results obtained for various assumed measurement patterns. Voltage and current phasor measurements were assumed to have known noise component variance. The standard deviation of each voltage measurement [15] was assumed to be

$$\sigma_V = (0.0017\ f_{sv} + 0.005\ |V|) \qquad (23)$$

where f_{sv} is the full scale of a voltage measuring device, and $|V|$ is the magnitude of the measurement. Similarly, the current measurement in a line was assumed to have a standard deviation

$$\sigma_i = (0.0017\ f_{si} + 0.01\ |I|) \qquad (24)$$

where f_{si} and $|I|$ are the full scale value of the current measuring device and current magnitude respectively. Since all voltages are near 1.0 per unit, it was assumed that the full scale of each voltage measuring device f_{sv} is 1.2 per unit, whereas $|V|$ is 1.0 per unit. This makes σ_V for each voltage measurement 0.007 per unit.

The IEEE 118 bus system consists of a 345 kV network and a 138 kV network. It was assumed that the full scale for current measurements on the 345 kV network corresponds to 5.0 per unit (500 MVA flow), while the full scale for currents on the 138 kV network was assumed to be 1.5 per unit (150 MVA flow). Since these are the maximum flows on any of the lines in the base case, it is to be expected that many current measurements may actually have a smaller full scale value. Consequently, the results obtained with the assumed standard deviations for current measurement errors can be expected to be somewhat pessimistic. The assumed current measurement errors are thus

σ_i = 0.0085 + 0.01 $|I|$ for 345 kV lines, and

σ_i = .00255 + 0.01 $|I|$ for all 138 kV lines.

Many cases having one current measurement per line were studied in some of the simulations. As derived in the previous section, the exact gain matrix for such a case is less sparse and may be complex (although it is still constant), and consequently several approximations were tried in order to reduce the number of computations in the solution of equation (10). These approximations will be explained below in detail. However, one of the approximations involved is that of creating a pseudo-measurement for the current at the unmetered end of a line from voltage phasor measurements at its terminals. The standard deviation of error in a pseudo measurement of a current is related to the errors in the voltage measurements. If the current measurement I_{pq} is missing, it can be constructed as follows:

$$I_{pq} = y_{pq}(E_p - E_q) + y_{p0}E_p \qquad (25)$$

If E_p and E_q have errors with standard deviations of 0.007 per unit and E_p is approximately 1.0 per unit in magnitude, then

$$\sigma'_{i(p-q)} \cong 0.014\ |y_{pq}| \qquad (26)$$

where the prime represents the standard deviation for a pseudo-measurement.

It should also be noted that the phasor measurement technique described here provides measurements in a rectangular form. Similarly, the state-estimation is also performed in rectangular coordinates. However, it is more convenient to describe the errors in phasor estimates in terms of their magnitude and phase angles. For relatively small σ's (say less than 2 per cent) the distribution of errors in magnitudes and angles of phasors is Gaussian for all practical purposes if the errors in rectangular coordinate measurements also have a Gaussian distribution with a standard deviation proportional to the phasor magnitude. Therefore the results of the simulations are given in terms of σ's for state vector magnitudes and phase angles although the entire procedure is based upon measurements in rectangular coordinates.

Six variations in measurement patterns and approximations to the gain matrix G were studied. The IEEE 118 bus system has 186 lines and transformers. The base case load flow was assumed to represent the nominal state of the system. Each of the variant cases assumed the measurement noise of the nature discussed earlier. Fifty Monte Carlo simulations were run for each of the cases described below. In each case, the standard deviation of the errors in estimated voltage phasors for all buses and for all fifty runs were computed. The six variations are as follows:

(1) All voltage phasors (118) and all current phasors at both ends of all lines (372) are measured. This case represents the best possible performance that can be achieved for the assumed measurement errors.

(2) One hundred current measurements were eliminated at one end of 100 lines. The missing current measurements are replaced by pseudo-measurements having $\sigma'_i = 0.014\ |y_{pq}|$. The exact gain matrix was retained.

(3) Same as Case (2), with gain matrix approximated by a real matrix. All imaginary terms in G are set to zero.

(4) Pseudo-measurements used with current measurements at both ends (metered as well as unmetered end) were assumed to have errors with a standard deviation of $0.014\sqrt{|y_{pq}|}$. This is the geometric mean of the standard deviation at the two ends. This assumption makes the measured currents appear to be somewhat worse that they are, but in the process makes the gain matrix real.

(5) No pseudo-measurements of currents are used. The gain matrix G is computed exactly, and is complex.

(6) No pseudo-measurements are used. Imaginary part of G assumed to be zero.

Table I gives the results of the fifty Monte Carlo simulations for each of these variant cases.

As mentioned earlier, Case (1) is the best possible performance for the assumed quality of measurement system. Case (2) represents incomplete current phasor measurements and consequently the errors of estimation are somewhat higher than in Case (1). If current measurements are lost as assumed and replaced by pseudo-measurements, Case (2) represents the best

TABLE I

Results of fifty Monte Carlo trials.

Case No.	Standard Deviation of Voltage Mag. estimation errors (per unit)	Standard Deviation of Voltage angle estimation errors (degrees)
1	2.72×10^{-4}	2.50×10^{-2}
2	3.15×10^{-4}	2.99×10^{-2}
3	3.25×10^{-4}	6.10×10^{-2}
4	8.82×10^{-4}	2.53×10^{-2}
5	3.21×10^{-4}	3.00×10^{-2}
6	3.31×10^{-4}	6.10×10^{-2}

possible performance with the lost data. Cases (3) and (4) are alternative ways of handling pseudo-measurements while using a gain matrix which corresponds to a complete measurement set. As can be seen from Table I, the computational simplification made in (3) and (4) worsens the estimate, although the increase in the standard deviations is still quite reasonable. Cases (5) and (6) represent approximate techniques whereby no pseudo-measurements of currents are used. Case (5) results should be compared with those of Case (2). In both cases one hundred current measurements are lost. While Case (2) deals with them as pseudo-measurements, Case (5) accepts this loss of data and models the process accordingly. There is hardly any difference in the performance of the state-estimator with these two alternatives.

Finally, Case (6) modifies the error characteristics of the current measurements in order to make them balance the errors in pseudo-measurements and still retain the real gain matrix. There is a significant loss in performance with this procedure, although even this extreme measure produces state estimates with acceptable accuracies.

CONCLUSIONS

(1) Direct measurement of positive sequence phasors on a common reference is made possible by the advent of microcomputers for substation functions. The sampling clocks used at various locations must be synchronized to within a few microseconds in order to achieve the required precision in phase angle measurements. Many alternatives for meeting this need exist at the present time.

(2) Phasor measurements make the state estimation problem a directly solvable problem. The gain matrix is sparse, constant, and in most cases real.

(3) If some transmission element currents are metered at one terminal only, a few complex off-diagonal terms appear in the gain matrix. Several approximations were tried to avoid using the complex gain matrix. Pseudo-measurements of currents at the un-metered ends seem to be a reasonable approximation. However, in all cases tested the best performance is achieved when the actual complex gain matrix is retained.

(4) If no currents are measured, then the state estimate is the set of voltage measurements. In this case there is no data redundancy. The bad data identification problem - although not addressed directly in the paper - is aided by the measurement of element currents.

(5) In addition to being useful for state estimation purposes, phasor measurements have several other possible uses. For example it may be sufficient to monitor and track the phase angles at a few key buses to assess the margins of security at an operating point. The direct state-measurement thus lends itself to implementation of multi-level security monitoring of power systems.

In fact, the system dynamics can also be monitored by tracking the positive sequence voltage phase angles at key locations.

Yet another application of phasor measurements would be to assess the likelihood of voltage collapse on a system which is prone to severe VAR imbalance problems. [14] It may be that the French concept of 'Pilot Points' can be expanded to include phase angle measurements as a key parameter.

(6) Where expansion of the existing monitoring (state-estimation) systems is contemplated - for example into the portion of a network belonging to a different voltage class - the use of phase angle measurements as proposed here may turn out to be the most economical and efficient option for the expansion.

The authors intend to obtain experimental verification of the phase angle measurement principle through field tests, and to report on the results as well as on some of the other ideas presented in the paper.

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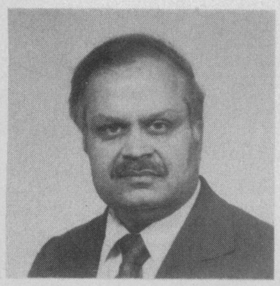
BIOGRAPHIES



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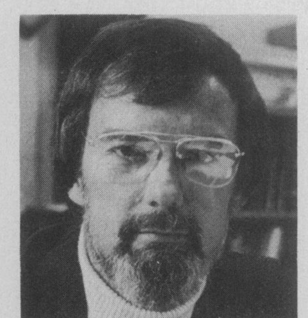

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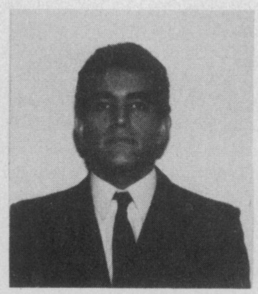

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