Measurement of Transient Electric Field Emission from a 245 kV Gas Insulated Substation Model during Switching

M. Mohana Rao†, M. Joy Thomas* and B. P. Singh**

Abstract – The transient fields generated during switching operations in a Gas Insulated Substation (GIS) are associated with high frequency components in the order of few tens of MHz. These transient fields leak into the external environment of the gas-insulated equipment and can interfere with the nearby electronics. Measurements of the transient fields are thus required to characterise the interference caused by switching phenomena in such substations. In view of the above, E-field emission measurement during a switching operation has been carried out for a 245 kV GIS model, using a resonant dipole antenna and D-dot sensor. The characteristics of the E-fields i.e., frequency spectra and their levels have been analysed and are reported in the paper. Suitability of the measurements has been confirmed by comparing frequency spectra of the measured and computed transient fields.

Keywords: D-dot sensor, Electromagnetic Interference (EMI), Gas Insulated Substations, Gas-to-air bushing, Resonant dipole antenna, Transient E-field.

1. Introduction

Gas Insulated substations (GIS) are based on the concept of complete encapsulation of all the high voltage (HV) energized parts in a grounded enclosure with compressed SF_6 (sulphur hexafluoride) gas as the insulating medium between the two. It is reported that, Very Fast Transient Over-voltages (VFTO) are generated during switching operations of disconnector switch (DS) or circuit breaker (CB) in such substations. The transient over-voltages and the associated Very Fast Transient Currents (VFTC) could have a rise time of 4 to 20 ns. The transient current magnitudes are in the order of a few kA depending on the rated voltage of the substation, location of the switch operated in the GIS etc. [1]. The transient voltages and currents radiate electromagnetic (EM) fields during their propagation along the high voltage gas insulated bus. Hence, GIS behaves as a coaxial waveguide for EM fields generated within the system. These transient fields in turn leak into the external environment through discontinuities such as SF_6 gas-to-air bushing, non-metallic viewing ports and other apertures present in the substation equipment. The transient fields further interact with the control circuitry and induce transient voltages up to a few kV depending on their characteristics like field levels, frequency content, GIS configuration etc. [2]-[3].

Malfunctioning of the primary/secondary equipments have been reported by many authors during switching operations in substations due to the induced voltages in the control circuitry [2]-[4]. Traditionally, substation's high voltage equipment and its control / protection equipments have been treated as separate systems. The GIS primary equipment consists of the high voltage apparatus that performs the primary functions of the substation such as switching, short circuit current interruption, measurement and isolation. The term secondary technology covers all the individual components that make up the protection, control and measuring equipment. These secondary equipments/ low voltage circuits are affected by the radiated EM field emission from the GIS modules during switching operations. For reliable operation of these equipments, the susceptibility level of the same must be above the level of the disturbance with a sufficient margin. Hence, measurement and characterization of the transient fields have of utmost importance to design the required protection for the low voltage equipment from interference related problems.

In this paper, the transient E-fields leaking out from a 245 kV GIS model during a simulated switching operation have been measured using a resonant dipole antenna and D-dot sensor. The transient E-field signal is captured both in time and frequency domain using a high bandwidth CRO and a spectrum analyzer respectively. The limitation of the resonant dipole antenna for the measurement of transient E-fields is analyzed and reported. Finally, the

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characteristics of the transient fields, which are measured using the D-dot sensor, have been studied at various distances from the bushing.

2. Transient fields

In a gas Insulated substation, each switching operation produces multiple electromagnetic field transients whose magnitude depends on the type of the switch being operated, transient current level, location of the field measurement with respect to the HT conductor of the GIS etc. In general, transient magnetic field follows the very fast transient current waveform and the transient electric field is proportional to integration of the transient current. However, due to the presence of metallic structures and multiple reflections between the grounded metallic enclosure and the ground plane, electric field waveforms also damp out to zero in a few μs unlike in a conventional air insulated substation. The amplitude of transient E-fields is generally in the range of tens of V/m to hundreds of V/m. The published data [2]-[3] shows that the peak amplitude could be even up to a few kV/m depending on the rated voltage of the substation and the observation point. In view of its importance, the authors have computed the transient fields for the bushing model using modified Finite Difference Time Domain (FDTD) technique [5]. Fig. 1 shows the transient E-fields computed in a GIS during a DS operation. The observation point of these E-fields is just above the ground (h = 0.1 m) and at a radial distance (r) of 2 m from the bushing.

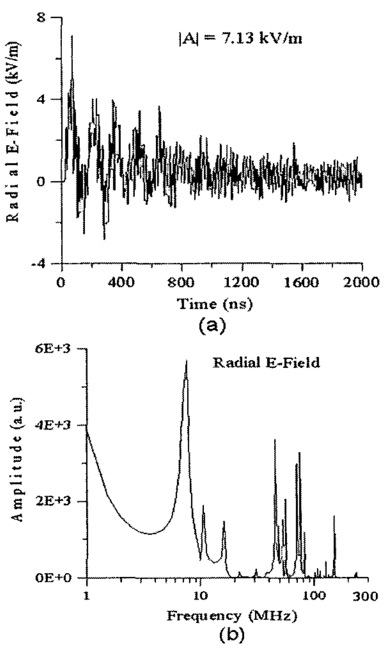

Fig. 1. Transient E-field emission from the bushing
(a) Time scale (b) Frequency scale

3. 245 kV GIS Model

The transient electric field emission measurements have been carried out for a 245 kV rated GIS model developed in the present study. The experimental set-up for the measurement of E-field emission is shown in Fig. 2. The experimental set-up used in the present study does not exactly match with the GIS configuration used for the computational study, the results of which are shown in Fig 1. Hence the amplitudes and frequency content of the measured fields will not be exactly matching with the computed waveforms. The model developed simulates the gas-insulated substation equipment and the measurement has been carried out in open space without possibility of much of reflection other than from the ground plane. A test transformer of 100 kV voltage rating has been used as a source for the experimental study. Aluminium pipe of circular cross section has been used for the HT connection between the test transformer and the bushing to minimize the corona. The gas chamber connected to the gas insulated bushing comprising of support insulator, HT conductor and the floating electrode. The support insulator made of epoxy material keeps the conductor at the center of the enclosure. The HT conductor and the floating electrode were assembled inside a gas chamber with an isolating distance (gap) of 12 mm, to create the required gas breakdown. SF_6 gas is filled in the system to a gauge pressure of 1 bar. The floating electrode is placed on the bottom cover of the gas chamber with the support of a nylocast insulator. The design of this insulator has been made in such a way that its flashover voltage is much higher than the breakdown voltage of the gas gap. Gradually increasing voltage is applied to the source side of the electrode system simulating a switch, which is placed in the gas chamber, until breakdown occurs. The arrangement generates VFTC due to the gas breakdown between the electrodes (load side floated) in each ac cycle depending on the source voltage (i.e., test transformer output voltage).

4. Measurement of Transient E-fields

The transient E-field emission from the GIS depends on the SF_6 gas breakdown characteristics and the electrode geometry. However, the variation in field amplitudes is highly dependent on the source voltage at the instant of the gas gap breakdown. A high bandwidth CRO (Model No. LC564A) has been used to capture the E-field waveform. The transient E-field level is observed to be a function of the height of the antenna above the ground plane. This may be due to varying emission levels from the bushing with vertical height. The transient fields leaking out from the GIS model is found to be increasing with increase in the breakdown voltage of the gas gap. The measuring antenna / sensor is located at different distances from the bushing (refer Fig. 3). During breakdown of the gas gap, transient fields generated due to VFTC leak out through the composite insulator housing. The grounded bushing structure contributes to a complex scattering environment and leads to an oscillatory E-field waveform. It is also noticed that the E- field level depends on the orientation of

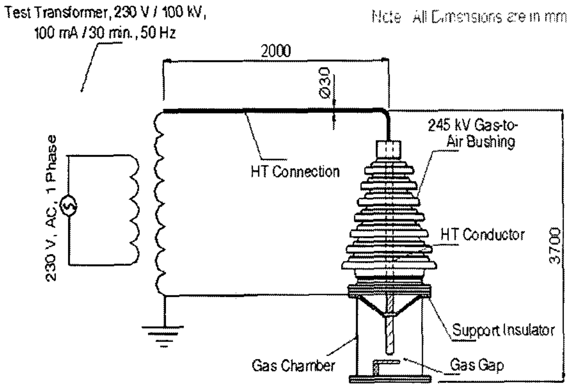

Fig. 2 Schematic diagram of experimental set-up.

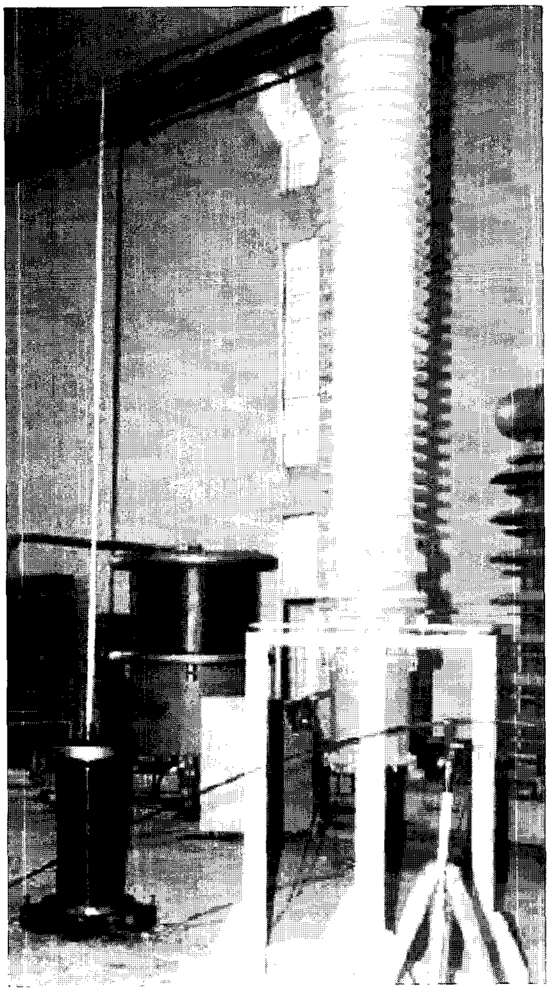

Fig. 3. 245 kV GIS model under study.

the antenna/sensor i.e., direction of the antenna arm with respect to the bushing. The relative position of the antenna/sensor w.r.t. the structure decides the E-field pattern at a particular distance.

4.1 Resonant Dipole Antenna

To measure the transient E-fields at different swept frequencies, a resonant dipole antenna has been placed at a radial distance of 3 m from the bushing. The orientation of the antenna is adjusted in such a way that the highest field level is measured for all the frequencies associated with the transient fields. The antenna is kept at a height of 2 m from the ground. This is to minimize the effect of the ground plane on the antenna response. The E-field emission measurement is carried out in the frequency range of 25 to 250 MHz. The Antenna Factor (AF) at different frequencies for the standard resonant dipole antenna used is shown in Fig. 4. Before performing the actual measurement of transient E-field emission from the GIS model, the ambient electromagnetic spectrum of the experimental setup GIS has been recorded. It is found that 62.4 MHz and 67.9 MHz are the dominant noise frequencies. Experiments were conducted with the GIS energized and switching operation is simulated by the breakdown of the SF_6 gas gap. The time varying E-fields at different frequencies are measured and are plotted in Fig. 5. By using the antenna factor, the output voltage at the terminals of the antenna has been converted into the transient E-field level. The time varying signal is captured for a total time duration of 1 μs. The frequency spectrum of the transient E-field signal for 25 MHz swept frequency is associated with frequency components up to 32 MHz (calculated using FFT technique). The E-field level is found to be significant up to 80 MHz frequency. For 100 MHz swept frequency, the E-field amplitude measured at a distance of 3 m from the bushing is found to be very low. In order to improve the signal-to-noise ratio, for the frequencies of 100 MHz and above, the transient E- field signal has been measured at a radial distance of 2 m from the bushing. For the E-field signal of 120 MHz, the dominant frequencies are still the same as that obtained at 100 MHz swept frequency and there is a possibility of frequency components in the order of 80 MHz with moderate amplitudes. At the scanning frequency of 200 MHz, the dominant frequency of 103 MHz also appears along with the frequency component of 186 MHz. This may be due to the higher amplitude of E-field for 103 MHz frequency-cluster than that for the frequency of the 186 MHz. More clearly, whatever may be the swept frequency in the range of 100 to 200 MHz, the E-field signal of 103 MHz frequency could be captured by the antenna. The attenuation rate of the measured transient E-fields with time is observed to be very fast compared to

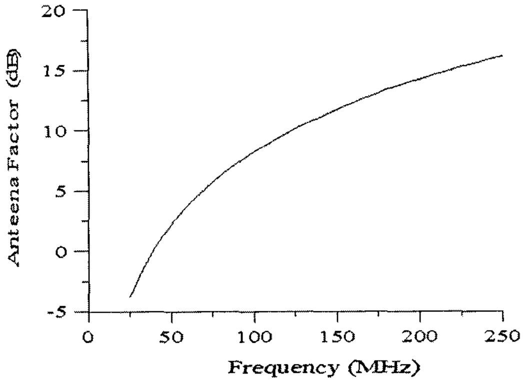

Fig. 4. Antenna Factor (AF) for a dipole antenna.

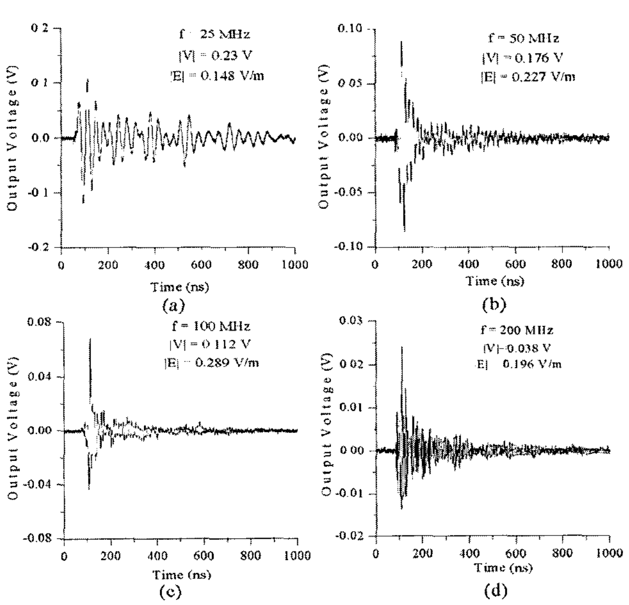

Fig. 5. Transient E-field measurement at different swept frequencies.

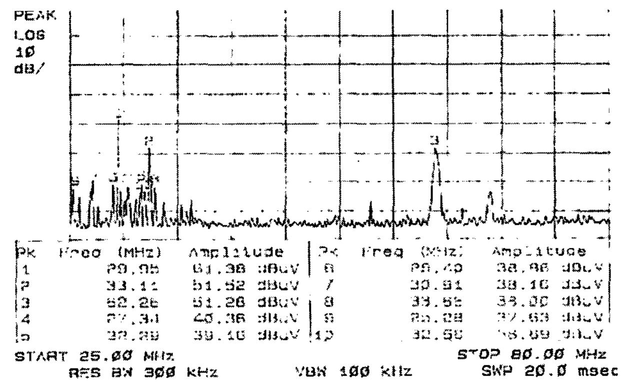

Fig. 6. Spectrum analyzer record at 25 MHz swept frequency.

the computed E-fields. This may be due to the additional propagation loss offered by the bushing support structure, test transformer etc. From the measurements, it is also clear that the time varying E-field signal at a particular swept frequency can also be associated with nearby frequencies depending on its contribution into the total E-field waveform. To verify the frequency content of the time varying E-field signal and hence the validity of the time scale measurement, the frequency spectra of the transient fields have been recorded at different swept frequencies using the spectrum analyzer (Model No. HP 8591E). Fig. 6 shows the frequency spectra of E-fields captured at a swept frequency of 25 MHz. From the results, it is observed that the frequency cluster is dominant up to 37 MHz starting from 15 MHz. It is also noticed that the amplitudes of the E-field for the frequency content beyond 80 MHz are observed to be very low as compared to the amplitude obtained at 25 MHz. There is observed to be a good agreement between frequency spectra of the time scale measurements and the spectrum analyzer records.

4.2 D-Dot Sensor

The resonant dipole antenna is able to identify the dominant frequencies of the transient E-field emission from a 245 kV GIS model during the simulated switching operation. However, the emission levels could not be quantified by antenna accurately. This may be due to the fact that the dimensions of the antenna are comparable to the wavelength of the transient E-field signal under measurement. More clearly, the response time of the antenna is much higher than the rise time of the transient E-field signal. Further, the antenna itself may disturb the field pattern substantially. Hence the dipole antenna may not be suitable enough to measure the E-field signals, which are transient in nature. In view of the above, an electrically small sensor i.e., D-dot sensor (known as transient field sensor) has been used for the present application. D-dot sensor is commonly used for the measurement of transient E-fields, which are of the order of few kV/m. The high bandwidth CRO has been connected to the sensor output terminals for recording the E-field waveform. The sensor is installed on an insulating stand, which can be adjusted to the required height. Table 1 shows the specifications of the D-dot sensor used for the present study. Measured voltage (V_o) is converted to radiated E-field by means of the following equation:

$$V_0 = RA_{eq} \frac{dD}{dt} \cos\theta \quad (1)$$

where, R is the terminating resistance, which is 50 Ω.

$A_{eq} = 0.001\ m^2$

θ = angle between E and the vector normal to the sensor ground plate, which is equal to zero for normal incidence.

D = Electric Flux Density in C/m^2 and $D = \varepsilon_o E$

By using the above parameters, eq. 1 can be converted in terms of E-field, which is as follows:

Table 1. Specifications of the D-dot sensor

S.no.	Parameters	Specifications
1	Equivalent area of sensor	0.001 m^2
2	Maximum output	250 V
3	Frequency response	> 3.5 GHz.
4	Model No.	ACD-7(R)
5	Make	EG&G

$$\frac{dE}{dt} = \frac{20V_0}{\varepsilon_0} \qquad (2)$$

Fig. 7 shows a view of the 245 kV rated bushing model with D-dot sensor. From the figure, it is seen that the sensor is oriented normal to the radial E-field emission from the bushing. Further, the sensor is located at a height of 2.2 m from the ground plane on an insulating stand so that it is on par with the height of the grounded flange of the bushing above the ground. To quantify the attenuation of transient fields with distance, E-field measurement has been carried out at various radial distances from the bushing (refer Fig. 8). The left side figures are the voltages measured at sensor output terminals, using a high bandwidth CRO. The right side figures are the equivalent transient E-field waveforms obtained, by integrating the corresponding left side figure with suitable multiplication factor (refer eq. 2). For this purpose a software code based on numerical integration has been developed and used. From the figure, it is seen that the E-field levels are in the order of 150 V/m depending on the radial distance of the sensor from the bushing. It is important to note that the present measurement is made at scale down voltages to understand the E-field waveforms generated during switching. The transient E-field level decreases with increase of the distance from the bushing. Further, the source and the load side voltages at the instant of breakdown decide the transient E-field amplitude for a particular GIS model. In the actual disconnector switch opening operation, the gas gap increases as time progresses and hence the breakdown voltage also increases till there is no further strike between the contacts. This results in transient E-field emission of varying amplitude in a GIS during service. To understand the dominant frequencies associated with the transient E-fields, frequency spectra have been calculated for the E-fields obtained at various radial distances from the bushing model and are shown in Fig. 9. From the figure, it is evident that the frequency components of the E-fields are observed to be dominant up to 45MHz only and beyond that there is a significant reduction in the amplitude. Further, the dominant frequencies may not change with radial distance from the bushing considerably. However, the transient E-field waveform is observed to be dependent on the observation point. In order to get better frequency spectrum for the transient field waveform of limited data (i.e., 1 μs), zero padding technique has been employed. From the figure, it is seen that the frequency spectrum is refined because of the zero padding to the transient field data (refer Figure 9(b) and 9(c)).

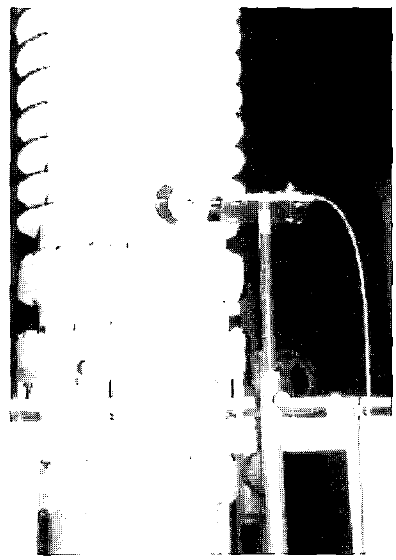

Fig. 7. Transient E-field emission measurement from the GIS model using D-dot sensor.

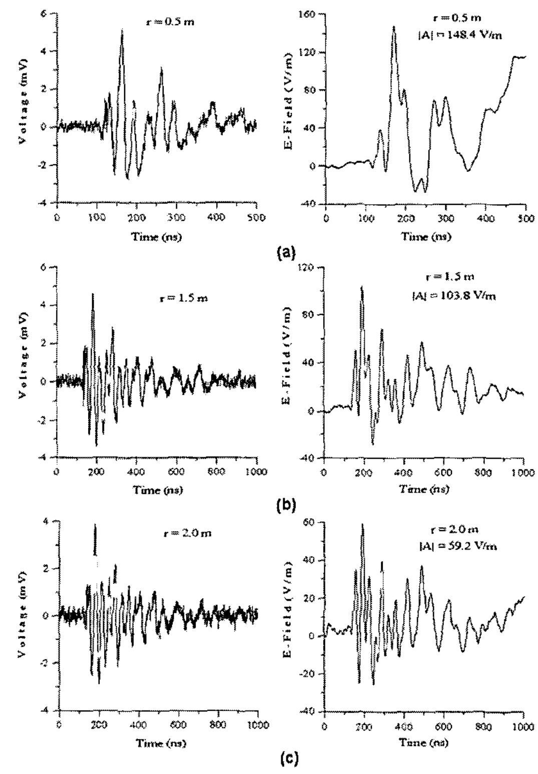

Fig. 8. Transient E-field measurement at various distances from the bushing using D-dot sensor.

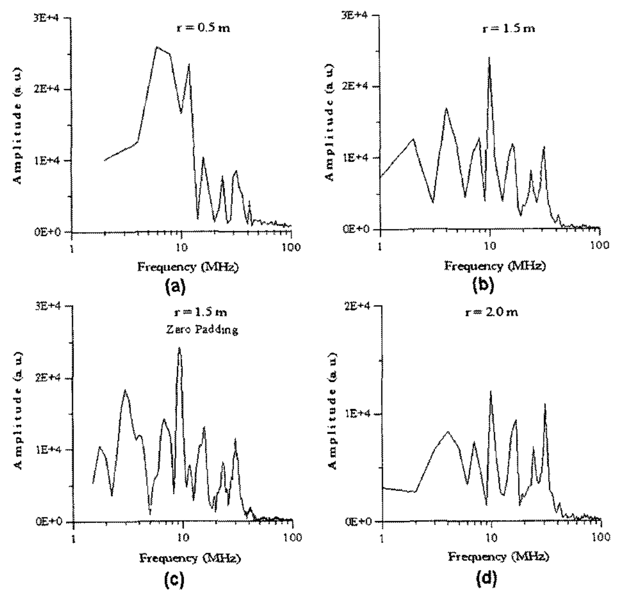

Fig. 9. Frequency spectra of the transient E-field emission from the GIS model.

5. Conclusion

The transient E-field emission from the 245 kV rated GIS model has been measured during a simulated switching operation by using a resonant dipole antenna and D-dot sensor. Measurement using a resonant dipole antenna shows that the transient E-field signal is found to be dominant up to 80 MHz and high frequency-cluster of 103 MHz is possible with marginal amplitude. The frequency content of the measured E-field is in the same order as the computed E-field waveform. Even though, the resonant dipole antenna is able to identify the dominant frequencies of the transient E-fields, it could not measure the E-field emission levels from the GIS model accurately. The transient E-field levels measured using D-dot sensor is found to be accurate and attenuating with increase of distance from the bushing. The frequency content of these E-fields is observed to be dominant up to 45 MHz only and beyond that there is a significant reduction in the amplitude.

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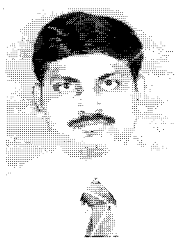

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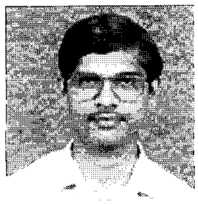

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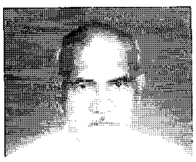

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