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Application of Magnetotelluric Technique in selection of Earth Electrode Sites for HVDC Transmission Systems: An example from NE India

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Abstract

Bulk electrical power transmission over distances exceeding 1000 km in HVDC (High Voltage Direct Current) mode is cost effective compared to transmission in AC mode and provides improved power system stability and power modulation control. A HVDC system requires specially designed earth electrodes at both ends of the transmission line with due considerations to the electrical resistivity of the ground in the vicinity of the electrode station. The design parameters of an earth electrode station require low near-surface electrical resistivity of the ground as well as low resistivity up to the depth of several kilometers so that the ground currents penetrate deep into the earth. Geophysical investigations using artificial source methods such as deep resistivity sounding pose logistic problems for these target depths. Magnetotelluric (MT) method is a very useful tool especially for the delineation of the electrical conductivity of the deep structure (up to 10 km depth) around an earth electrode site. We have carried out detailed investigations of some potential HVDC ground electrode sites employing magnetotelluric method to assess the suitability of these sites for the construction of earth electrode stations for India's first ±800 kV, 6000MW HVDC multi-terminal transmission systems. MT method has been found to be a very useful tool for this purpose.

Introduction

The use of HVDC (High Voltage Direct Current) technology for transmission of bulk electrical power over long distances is more economical as compared to transmission in AC mode as the transmission losses in HVDC system are significantly lower. Besides, HVDC transmission has other advantages such as controllability, improved power system stability and power modulation control. (Nayak *et al.,* 2008). HVDC systems are designed to operate in bipolar mode, monopolar metallic return and monopolar ground return modes. In monopolar ground return mode significant amount of current is continuously injected into the ground. Thus, HVDC systems require specially designed earth electrode stations associated with the converter terminals of the HVDC transmission system. The earth electrodes provide an earth return circuit, facilitating the flow of current into the earth. The design parameters of earth electrodes require consideration of the electrical conductivity structure of the subsurface at and around ground electrode sites. For a proper design, it is important to ensure that the site selected for the ground electrode is electrically conducting at shallow depths.

It is important to ensure that the site selected for the ground electrode should have low surface electrical resistivity to keep the step and touch potential within safe limits (Thunehed *et al.,* 2007). It is also necessary to ensure that the injected currents penetrate deep into the structure of the earth so that the grounding resistance/ potential rises in the vicinity of the electrode are within acceptable limits. This ensures that the ground currents do not cause corrosion of buried pipelines and do not enter the neutrals of transformers installed in the close vicinity of the Electrode station. For this purpose it is important to know the electrical resistivity structure of the site up to the depth of 5 to 10 km.

The electrical resistivity of the ground can be measured by various methods depending on the current transmission requirements of a HVDC project. Estimates of the near surface resistivity in the depth range of less than 100 m, required for the design parameters of an earth electrode, can be obtained by conventional Schlumberger, Wenner, dipole-dipole, pole-dipole methods. In recent years, electrical resistivity tomography (ERT) technique has become a very useful tool in imaging the subsurface resistivity structure and provides information about the lateral heterogeneities at a high resolution (Barker and Moore, 1998).

Delineation of the resistivity structure within a radius and depth of up to a few tens of km around an earth electrode site remains a difficult task for an active source resistivity survey. Attempts have been made to obtain this information through deep DC electrical resistivity sounding (DRS) methods (Singh *et al.,* 2005). In this method, a strong current of about 20 Amp at more than 3000 V is injected in to the ground at a current electrode separation of up to 10-15 km. A current electrode separation of 10-15 km can provide the resistivity information of about 2-3 km depth. To reach a depth exceeding 2-3 km, one needs a much stronger current injection and electrode spacing, making logistics extremely difficult for use in the investigation of the deep structure as required for a HVDC system.

In contrast, magnetotelluric (MT) method utilizes natural sources of electromagnetic (EM) field to delineate the electrical resistivity structure of the earth. These natural sources are mainly located in the magnetosphere and ionosphere, separated from the earth’s surface by the non conductive atmosphere. The earth being conducting, these natural sources induce secondary fields in the earth. Natural EM fields are time-varying and dominated by the wave phenomenon in the atmosphere but within the earth, these fields are controlled by diffusion process due to the high conductivity of the earth. Natural EM fields contain a wide spectrum of signals. Therefore, it is possible to get the deeper resistivity information by recording low frequency content of the signal which in turn means a longer duration of MT time series recording. For a sufficiently long time series record (a week or more) it is possible to reach the depth of more than 50 km over a moderate conductivity ground.

We opted to use MT method to investigate the deep resistivity structure of earth electrode sites because of this advantage. There is also logistic advantage, especially in the case of deeper (more than a couple of km) investigations. We have carried out detailed investigations of many earth electrode station (EES) sites for the first ±800kV, 6000 MW multi-terminal HVDC system being constructed by Power Grid Corporation of India to transmit electric power from North Eastern part of India to the Northern region. The length of the bipolar HVDC transmission line is about 1800 km and it passes through areas of high pollution levels. These have been discussed in Manglik *et al.,* (2008a, 2008b) and Nayak *et al.* (2008). In this paper, we present an example of the application of MT method in the selection of an earth electrode site in NE India (NER). We have also used ERT technique to delineate the shallow resistivity structure of the site. We suggest that a strategy appropriately combining MT and resistivity imaging surveys can be useful in testing the suitability of an earth electrode site.

Geological Considerations

Local geological and tectonic conditions are important in the selection of a suitable EES site. Areas having surface exposures of granites, gneisses etc or the areas known to have basement at shallow depths, inferred by other geophysical methods, should be avoided as these rocks in general have very high electrical resistivity. In some areas, it may be possible to encounter high-resistivity basement beneath the sedimentary cover. Here, we present an example from Assam to show the importance of integration of MT and ERT methods in site election for EES.

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Assam is dominated by the alluvial plains of Brahamputra and Barak - Surma rivers. Tectonically, it lies mainly between the Main Boundary Thrust (MBT) and Dauki and Disang thrusts (Fig. 1). Geologically, the rocks of Assam region extend in age from early Proterozoic to the recent and present day alluvium (Dasgupta and Biswas, 2000). Surface exposures of rocks of these extreme ages can be seen along the Brahamputra valley but most of the intermediate age rocks are buried deep under the alluvium. The oldest rocks, seen in the Shillong Plateau, consist mainly of granitoid gneiss, hornblende-biotite gneiss and biotite-cordierite gneiss of early Proterozoic age (< 2.5 billion year before present (GaBP)). These metamorphic rocks extend from eastern Shillong to Mikir Hills in a 50 km wide and 200 km long belt. These rock groups are intruded by some basic and ultrabasic rocks some of which are as young as Cretaceous period. These early Proterozoic rocks show high electrical resistivity. Younger sedimentary sequences were deposited on the above crustal mass. Younger age rocks consisting mainly of shale, limestone, sandstone have been encountered in many drill holes. The thickness of younger sedimentary rocks increases towards the north as the basement rocks dip northward along the Himalayan thrusts system consisting of Tsangpo suture, Main Central Thrust (MCT), Main Boundary Thrust (MBT), and Tipi Thrust.

Magnetotelluric Method

The method was proposed by Tikhonov (1950) and Cagniard (1953). Extensive development has taken place in this field ever since in terms of data acquisition systems, time series processing and modeling and interpretation tools. These developments have been described in great detail in many text books and research articles. Therefore, we only briefly outline the method here.

The theory of magnetotelluric method is based on the Maxwell's equations which relate electrical and magnetic fields. These equations, after some mathematical steps, lead to the Helmholtz equation (Cagniard, 1953)

$$\Delta[E(f),B(f)] = i\omega\mu\sigma(x,y,z)[E(f),B(f)], \tag{1}$$

in the frequency domain under the plane wave approximation ignoring the wave number term. Here, (E,B) are electric and magnetic fields in frequency domain (f), Δ is the Laplacian operator, and ω,μ,σ are radial frequency ($\omega = 2\pi f$, f being the frequency), permittivity of space, and electrical conductivity, respectively. From the above equations, it can be seen that MT fields are frequency and electrical conductivity dependent. When the conductivity of the rocks is not frequency dependent, a change in conductivity at a certain frequency is related to variations in conductivities of different rocks. From eq.1, it is possible to derive an expression for the skin depth, the depth at which the field strength exponentially decays to e^{-1} thereby giving an effective estimate of the depth of signal penetration, for a known frequency, f , and electrical conductivity, σ , as:

$$d_{skin} = (\omega\mu\sigma/2)^{-1/2} \quad = 503(f\sigma)^{-1/2}. \tag{2}$$

It can be seen from eq.2 that, for a constant electrical conductivity of the earth, the depth of signal penetration increases with decreasing frequency. Therefore, we need lower frequency signals to get deeper information. Similarly, for a constant frequency, the skin depth decreases with increasing conductivity of the medium, implying that for a conducting zone the eddy currents are sustained within the zone.

The vector nature of electromagnetic fields enables us to estimate the tensor form of the electrical conductivity structure by measuring these components in orthogonal directions. A typical MT measurement involves acquisition of 5 components time series data consisting of three magnetic $[H_x, H_y, H_z]$ and two electric $[E_x, E_y]$ components. These time series are then processed and converted in spectral form to estimate the impedance tensor Z, a complex quantity, which relates electric field to the magnetic field as

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} B_x \\ B_y \end{bmatrix}. \quad (3)$$

Once the impedance tensor is obtained, it is easy to calculate the apparent resistivity and apparent phase in horizontal orthogonal directions by using:

$$\rho_{xy}^a = \frac{\mu}{\omega}\left|Z_{xy}\right|^2, \quad \phi_{xy}^a = \arctan\left[\frac{\mathrm{Im}(Z_{xy})}{\mathrm{Re}(Z_{xy})}\right] \qquad \rho_{yx}^a = \frac{\mu}{\omega}\left|Z_{yx}\right|^2, \quad \phi_{yx}^a = \arctan\left[\frac{\mathrm{Im}(Z_{yx})}{\mathrm{Re}(Z_{yx})}\right]. \quad (4)$$

We obtain information about the variation of apparent resistivity and phase with frequency from the recorded time series of electric and magnetic field components and then invert these data sets to construct the resistivity-depth section as well as lateral variations in the subsurface structure.

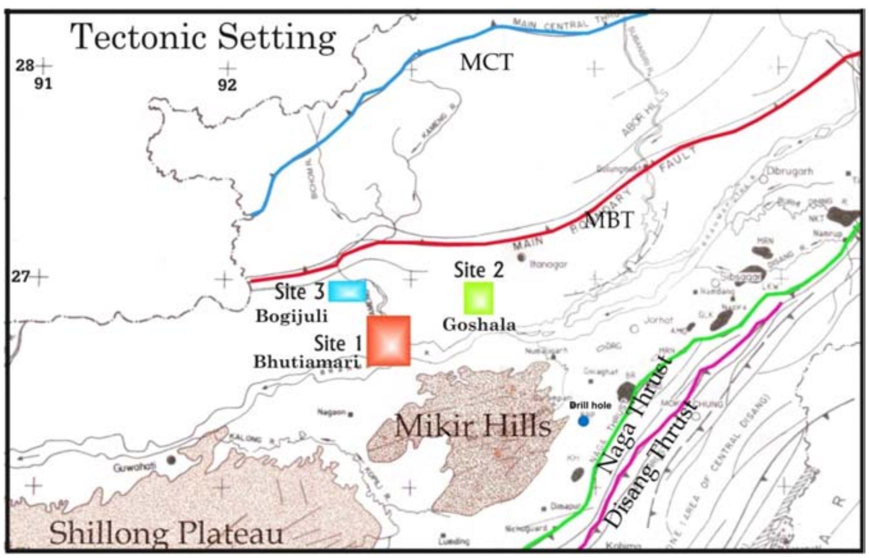

Fig.1: Location of earth electrode sites in north-east India (NER) superimposed on the tectonic map. Also shown is the location of a drill hole (blue circle) east of Mikir Hills. (Modified after Dasgupta and Biswas, 2000)

Survey Design

MT signals are very weak, of a few tens of milli-Volts. Therefore, site selection for an MT station requires the site to be away from any artificial source electrical and cultural noise. This is crucial for acquiring good quality MT data. This, however, is not possible to achieve always due to local logistics and constraints. In a populated area, it is often difficult to get a set of relatively quite sites for MT investigations. Keeping in view these constraints we planned an optimum survey design (dark circles in Fig. 2) to obtain the deep resistivity structure of an area of 10 km radius around an EES site. In this design, the area was covered with 13 MT soundings distributed along two orthogonal profiles from the centre of the site. A more rigorous design may include many more points within all the quadrants, especially when the radius of the circle from the centre of the site becomes large (gray circles in Fig. 2).

At every station time series data were acquired for minimum of one day to achieve the desired depth of investigation, assuming moderately conducting ground conditions. This planning was done to ensure that we have apparent resistivity data of up to 5s period with good signal/noise (S/N) ratio. MT signals are very weak in strength in the period range of 3-10s also known as the dead band rendering a reliable estimation of the apparent resistivity in this band difficult. A large number of stacks, and thus a longer time series, therefore are required to extract an acceptable estimate of the apparent resistivity and phase for this range of period. In some cases with, very quiet and electric noise free sites, it was possible to extract the information at much lower frequencies.

Wide-band MT equipment used in field surveys consists of 6-channel data acquisition unit ADU-06, three highly sensitive magnetic induction coils MFS-06, and GPS module (M/s Metronix GmbH). We used commercial software, Mapros (M/s Metronix GmbH) to analyse time series data and generate apparent resistivity curves. Resistivity inversion was carried out by using commercial software, WinGLink (M/s Geosystem SRL).

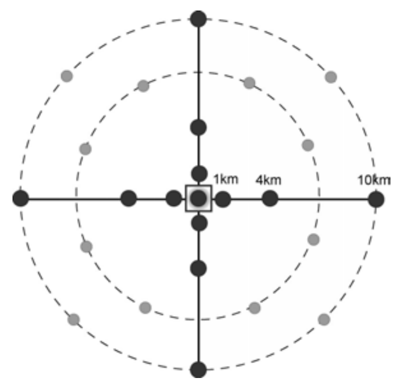

Fig. 2: A layout of the MT survey for HVDC ESS investigation in NER.

The EES area of 600m x 600m at the intersection of the two MT profiles (shaded rectangular area in Fig. 2), needed to place the electrode ring, was investigated for the detailed electrical resistivity structure up to a depth of 100 – 150m. This shallow resistivity information is needed mainly for the electrode design. We used 7 multi-electrode DC profiles at 100m separation to image the shallow subsurface electrical resistivity structure up to the depth of 150 m. Each profile was of 790 m length and consisted of 80 electrodes at 10 m electrode spacing, giving a penetration depth of more than 120m. The data in Wenner-Schlumberger conFiguration were acquired using multi-electrodes resistivity imaging system (LUND imaging system, M/s. ABEM limited, Sweden). This system allows automatic recording of data for different electrodes conFigurations. Resistivity inversion was done using RES2INV program.

Results

In this section, we present an example to highlight the application of MT method in EES site selection for an HVDC system. We also show the significance of incorporating the regional geological and tectonic information during the identification of a potential site. We investigated three sites in NER. The first investigated site (Site-1) is located near Jamagudi in Assam about 6-7 km north of the river Brahamputra (Fig. 1). The geology of the area is constituted of a thick pile of alluvial soil without any rock exposure in the vicinity and has almost flat topography. The soil resistivity is also less than 100 Ohm.m. Thus, the site appeared to be favorable for the placing of an earth electrode. We carried out 13 MT soundings at this site as per the conFiguration shown in Fig. 2.

The results of MT sounding at the centre of the site are shown in Fig. 3. At this station, we have obtained almost similar curves for ρ_{xy} and ρ_{yx} in the high frequency range indicating that the shallow resistivity structure is fairly uniform and one-dimensional in nature. We inverted smooth invariant apparent resistivity and phase data. The results (Fig.. 3) show the presence of about 200m thick top layer of 125 Ohm-m resistivity. A conducting zone of about 1,100m is present below this layer. Further deep, the resistivity increases drastically to more than 10,000 Ohm.m at the depth of about 1,300m, indicating the presence of highly resistive basement rocks which extend to the depth of 10 km. The presence of this high resistivity layer was consistently seen below all the MT locations around the earth electrode site, suggesting that the site does not meet the requirement of low resistivity of the ground up to the depth of 5 to 10 km. In the present case, even though the shallow resistivity structure was favorable for an ESS site, the deep resistivity structure obtained by MT helped in decision making on avoiding the site for the earth ground station.

There are no drill data available from the nearby areas. The high resistivity basement encountered at the depth of 1730m (Dasgupta and Biswas, 2000) in a drill hole ESE of the site (blue circle in Fig. 1), however, supports our inference about the deep resistivity structure of the investigated site. This information and existence of high resistive granitic rocks of Shillong Plateau and Mikir Hills further south support our results of deep resistivity investigations.

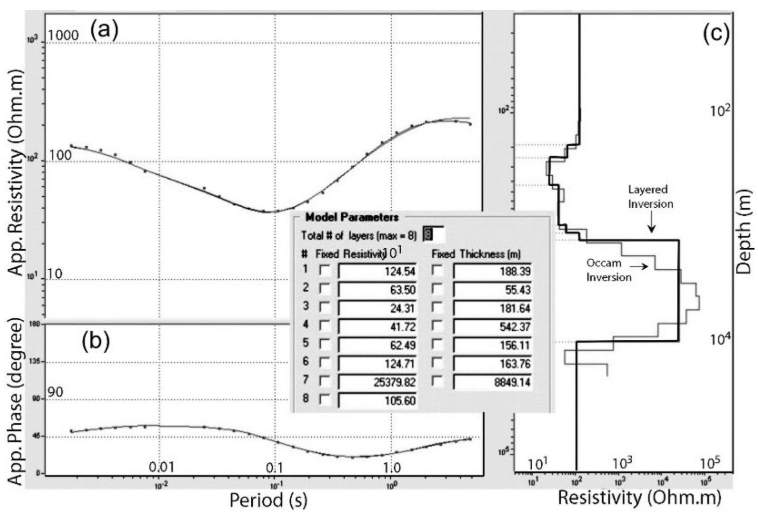

Fig. 3: (a) Apparent resistivity, (b) apparent phase, and (c) obtained resistivity structure after 1-D smooth invariant inversion for a MT station at site-1. In (a,b) dots show observed data and solid curves correspond to the synthetic data for the models shown in (c). Both Occam and layered inversions were performed.

We further analyzed the geological, tectonic, and other geophysical information of the Assam region to identify other potential sites. The flexure of the Indian lithosphere by the load of the Himalaya caused thickening of the resulting fore-deep basin towards the Himalayan collision zone. The Indo-Gangetic sedimentary basin is formed by such a process and the flexure of the Indian lithosphere is clearly discernable from the Bouguer gravity anomaly (BGA). For the Assam region also the Bouguer gravity anomaly supports this view as the E-W trending contours of BGA become more negative in the northward direction (Dasgupta and Biswas, 2000). Therefore, we anticipated that the thickness of relatively less resistive sediments/ sedimentary rocks should increase towards the foothills of the Himalaya.

Two sites (Site-2 and Site-3 in Fig. 1) were identified after analyzing the above geological and geophysical information and taking into consideration the logistic constraints. MT investigations were carried out at both these locations but with a reduced number of MT stations to get an idea about the general deep resistivity structure. We describe below the results of site-3, which was located near the Balipara sub-station of PowerGrid in Assam. The data were acquired along two orthogonal profiles passing through the centre. Each profile consisted of only four MT stations. The results of MT investigations revealed the presence of a conducting zone of about 3.2–3.6 km average thickness. The resistivity further deep was also not as high as that encountered at site-1. The results of 2-D inversion of MT data along the E-W profile are shown in Fig. 4. Also superimposed are columns of 1-D interpretation of the data. These results show the presence of a conductive zone up to the depth of 4-5 km.

Since the deep resistivity structure was acceptable, we next investigated the EES site covering an area of 600 x 600 m^2 by ERT technique to obtain the detailed shallow resistivity structure. The average resistivity model of the site consists of a 20m thick resistive layer (resistivity up to 500 Ohm-m), a moderately resistive layer (100-300 Ohm-m) between 20-80m depth, and a conducting layer (<100 Ohm-m) below that. The results also reveal the lateral variations in the shallow resistivity structure of the area. A 2-D resistivity image along a profile is shown in Fig. 5. The identification of the presence of an about 20 m thick resistive near-surface layer will be helpful in the decision making of the design parameters of the earth electrode.

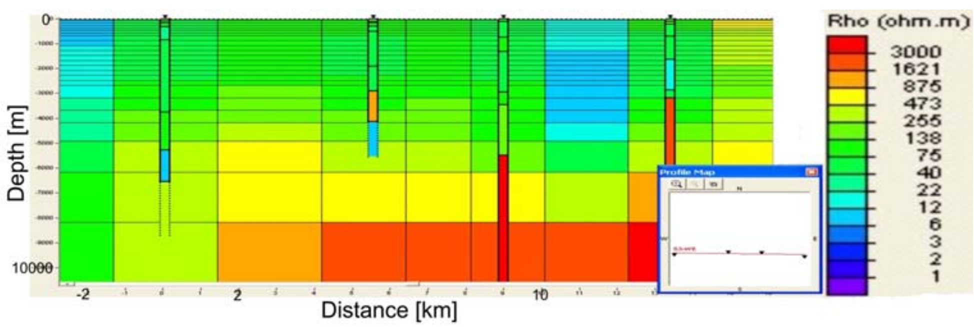

Fig. 4: Inverted 2-D resistivity section along a W-E profile for site-3. Also shown are columns of 1-D structure obtained for each of the MT stations.

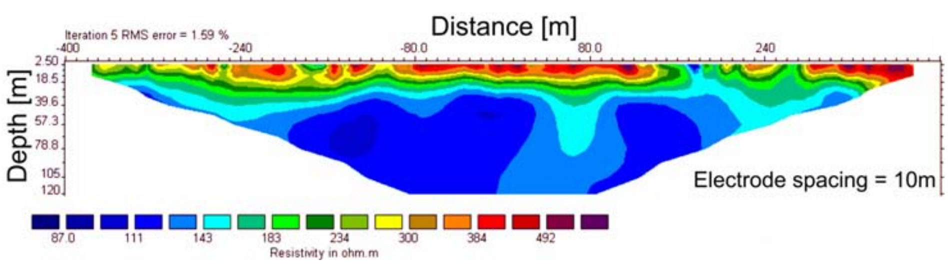

Fig. 5: ERT image along one profile at site-3.

Conclusions

Electrical and electromagnetic methods are very useful in the delineation of the electrical resistivity structure of the ground over a wide depth range. For the target depths ranging from a few hundreds meters to about 2-3 km DC resistivity methods may be used. However, deep DC surveys become logistically difficult for deeper investigation depths due to the requirement of large dipole length and current amplitude. MT method, based on the induction of natural EM fields, overcomes these logistic problems and may be effectively used to investigate the deep subsurface electrical resistivity structure of an EES site for a HVDC system. It is demonstrated by the results presented in previous the section. Setting up of a MT station needs only a small clear area. Thus, MT method is a useful tool for the investigation of the deep resistivity structure as required by large

HVDC projects aimed at transmitting current at several hundreds kV rating over long distances. MT investigations combined with DC resistivity imaging surveys may be useful in testing the suitability of an earth electrode site as well as in designing the parameters of an earth electrode.

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