Geoelectric Strike Analysis from Magnetotelluric (MT) Data Using Swift and Polar Diagram Methods

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Abstract
The magnetotelluric (MT) method is commonly used to estimate the subsurface conductivity structure. From the point of view of computational resources availability, currently it is a common practice to perform a 2D MT inversion modelling of MT data measured along a profile. For that purpose, the geoelectric strike angle determination from MT data is essential. The geoelectric strike angle can be determined by rotational analysis of the MT impedance tensor. In this paper we compare geoelectrical strike angle from both Swift method and polar diagram analysis by plotting the results as rose diagrams. The results from rotational analysis suffer from 90° ambiguity in the structural direction. Along with information from the regional geology to resolve the ambiguity, the profile for MT 2D modelling can be more appropriately selected. We used MT data from a geothermal prospect to illustrate our exercise.

1. Introduction
Magnetotelluric (MT) method is commonly used in exploration to estimate the subsurface conductivity structure. Conductivity can be correlated with temperature effect to rock formations in a geothermal field. Therefore, MT is considered as one of the most effective method to image resistivity distribution in a geothermal prospect [1]. In general, MT data can be modelled in 1D, 2D, or 3D for various exploration stages. However, 2D MT modelling is often performed for its relatively “inexpensive” computational cost (compared to 3D modelling) which still results in relatively realistic models [2]. In such case, geoelectric strike angle determination is essential to select an appropriate profile direction.

It is a common practice, especially in Indonesia, to model MT data for 2D resistivity structure along profiles perpendicular and parallel to a regional structure supposed to be known. Without directional analysis of MT impedance tensor, such practice can lead to ambiguous determination of TE- and TM-mode data for 2D MT modelling. This paper illustrates MT impedance tensor analysis for geoelectric strike and profile determination using conventional Swift and polar diagram methods. The MT data from a geothermal area in Sumatera (Indonesia) are modelled in 2D using WinGLink software.

2. MT Strike Analysis
In the frequency domain, amplitude and phase relationship between horizontal components of the electric (E) and magnetic (H) fields are represented by the impedance tensor Z defined as [3],

\[
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix} = \begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{bmatrix} \begin{bmatrix}
H_x \\
H_y
\end{bmatrix}
\]  \hspace{1cm} (1)
which applies in general to 3D resistivity distribution or \( \rho(x, y, z) \). In 1D or layered earth, resistivity varies only with depth. The diagonal components of the impedance tensor, and are zero, and the off-diagonal components are equal in magnitude but have opposite signs. In 2D earth case, resistivity varies with depth and one horizontal direction, while it remains constant in the other horizontal direction. This direction in which the resistivity is constant is called the geoelectric strike. The impedance tensor in 2D case is decoupled into two modes where \( x \)-axis is parallel to strike and \( y \)-axis is perpendicular to strike, or the other way around. The mode with electric field parallel to strike is called transverse electric (TE) mode and when the magnetic field parallel to strike is called transverse magnetic (TM) mode.

In general, MT data can be collected with any coordinate system orientation and it is rarely in the strike direction. To perform 2D analysis, MT data need to be rotated to a coordinate system that applies to TM or TE modes. Rotation of \( \mathbf{Z} \) from a coordinate system through an angle \( \alpha \) will result in \( \mathbf{Z}' \) expressed by,

\[
\mathbf{Z}' = \mathbf{R}(\alpha) \mathbf{Z} \mathbf{R}^{-1}(\alpha)
\]

with \( \mathbf{R} \) is the rotation matrix, defined as,

\[
\mathbf{R} = \begin{pmatrix}
\cos \alpha & \sin \alpha \\
-\sin \alpha & \cos \alpha
\end{pmatrix}
\]

Although, other source of information such as regional geological strike can be used, it still needs to be demonstrated that the coordinate system chosen is supported by the geoelectrical strike obtained from MT data. In addition, MT tensor impedance rotation and TE- and TM-mode determination are also of prime interest.

In our research, the geoelectric strike analysis was performed by using conventional Swift and polar diagram methods. To obtain the direction of the structure in 2D, the so-called Swift method involves maximizing \( |Z'_{xy}(\alpha)|^2 + |Z'_{yx}(\alpha)|^2 \) or minimizing \( |Z'_{xx}(\alpha)|^2 + |Z'_{yy}(\alpha)|^2 \), both will give the same direction of the structure \[4\]. Other method that can be used to obtain the geoelectrical strike is the polar diagram. The polar diagram illustrates graphically the amplitude of tensor elements as function of the rotation angle \( \alpha \). This method involves evaluating the minimum and maximum of tensor elements \( Z'_{xx}(\alpha) \) and \( Z'_{xy}(\alpha) \) respectively, corresponding to the geoelectric strike.

For that purposes we implement the MT strike analysis as an integrated program formulated in MATLAB R2016a. Incremental rotations are performed to \( \mathbf{Z} \) for each period so that \( \mathbf{Z}' \) is obtained. Rotated tensor elements are evaluated with Swift and polar diagram method to obtain \( \alpha \). The process is repeated for different periods of \( \mathbf{Z} \). The rotation angles \( \alpha \) collected are plotted in rose diagrams for each method in each site. Rose diagrams represent the number of occurrences of \( \alpha \) within an interval of angle from which the dominant angle can be interpreted as the geoelectric strike. Strike directions obtained from both Swift and polar diagram methods contain \( \pm 90^\circ \) ambiguity. This inherent ambiguity is resolved by validating the results with the regional geology of the area.

### 3. 2D Modelling

We also performed 2D modelling using WinGLink software. Both TE- and TM-mode MT data were used in the inversion process as they both complement each other \[5\]. In this case, mesh grid was designed based on basic rules described by Simpson and Bahr \[6\], i.e. mesh at the center of the area of interest is denser and become sparser outwards.

The algorithm employed in WinGLink is by discretizing the half space into rectangular blocks of different dimension with each block assigned a constant resistivity. The forward modelling is computed by using the finite difference technique. The inversion finds smooth solutions using non-linear conjugate gradient (NLCG) method to match the MT data. The NLCG method is used to minimize an objective function or commonly known as misfit with additional model roughness elements. Details on inversion with smoothness constrain implemented in the software can be found in Rodi and Mackie \[7\].
4. Results and Discussions

MT data for this research were acquired at a geothermal prospect located in Sumatera, Indonesia. The regional geology of the area is dominated by NW-SE structures associated with the Great Sumatra Fault Zone. Based on geoelectric strike analysis in each site, most sites have a similar dominant direction with the regional structure, especially when ±90° ambiguity is considered. The direction from geoelectric strike analysis of each site is plotted in Figure 1.

The geoelectrical strike analysis was also done for all stations, both for all periods and for certain range of periods (Figure 2). The latter is intended to analyse whether there are directional changes with depth in the area. The results from all period range (0.001 to 1000 sec.) show a relatively clear geoelectric strike direction, especially those from polar diagram analysis. They represent a strike direction of N150°E or N-30°W which is in a good agreement with the NE-SE regional structure of the area. Similar results are also obtained from Swift method with additional right angle ±90° directions from the main strike direction. More confident results are obtained from analysis for data at longer periods (10 to 1000 sec.) For short periods up to 10 sec. there is no distinct strike direction from both Swift and polar diagram methods. This tendency is generally observed in many areas showing dominant 1D or layered environment at a relatively shallow depth, i.e. no structural direction.

![Figure 1](image1.png)

**Figure 1.** Geoelectric strike at each site obtained using Swift method (left) and polar diagram method (right). The regional geology structures are in NW-SE direction.

The result of geoelectrical strike analysis was used to select profile direction and impedance tensor rotation for 2D MT modelling. Profiles are selected perpendicular to the direction of structure so that resistivity variations along those profiles are more representative of the 2D models. MT impedance tensor data were rotated to N330°E such that TE- and TM-mode data are obtained. Inversion modelling by using WinGLink software were done at two profiles, Line-1 and Line-2, and the 2D models are presented in Figure 3. Misfits of inverse models from Line-1 and Line-2 are 5.84 and 3.27 respectively, which are considered as decent.

Elevations in both profiles vary between 2500 to 1500 above mean sea level (msl). In general, the subsurface of the area can be distinguished into a conductive layer (less than 7 Ohm.m), a layer with moderate low resistivity between 7 to 50 Ohm.m and a layer with resistivity above 50 Ohm.m. All three layers can be interpreted as clay cap, transition zone and reservoir zone respectively. However, the layers, especially the conductive clay cap, are discontinuous that may be attributed to the heterogeneity of the surface layer up to a certain depth. In addition, the presence of local 3D heterogeneities manifested
as static shift distortions, that were not corrected in this research, may cause such discontinuity [6]. We do not have access to TEM data that could be used to correct the static shift. By considering results from analysis of other data (i.e. geology, geochemistry, well-log) our 2D MT model can be further interpreted with more confident (see Figure 3). For example, the layers are considered as continuous and the reservoir zone can be associated with zones of epidote and other high temperature minerals [8].

Figure 2. Rose diagrams from geoelectric strike analysis using polar diagram (left) and Swift method (right): (a) for the entire period range, (b) for 10-1000 sec. and (c) for 0.001-10 sec.
5. Conclusion
Geoelectrical strike analysis using Swift and polar diagram methods show satisfactory results and is in good agreement with the regional structure of Sumatera in NW-SE direction. Therefore, profile selection and MT impedance tensor rotation can be done appropriately prior to 2D MT modelling. Resistivity models at two profiles show representative resistivity variations of a geothermal prospect that are further confirmed by data from geology, geochemistry and well-log.

References
[1] Muñoz G 2014 Surv. Geophys. 35 101-122.
[2] Cumming W, Mackie R L 2010 Proceedings World Geothermal Congress 2010, Bali, Indonesia.
[3] Caldwell T G, Bibby H M and Brown C 2004 Geophys. J. Int. 158 457-469.
[4] Vozoff K 1972 Geophysics 37 98-141.
[5] Bedichevsky M N, Dmitriev V I and Pozdnjakova E E 1998 Geophys. J. Int. 133 585-606.
[6] Simpson F and Bahr K 2005 Practical Magnetotelluric Cambridge University Press.
[7] Rodi W and Mackie R 2001 Geophysics 66 174-187.
[8] Anonymous 2015 Unpublished Report.