Analysis and application of impedance polar diagram and zstrike rose diagram of magnetotellurics data in southern part of the Wayang Windu geothermal field

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Abstract. In this study, we determined the main direction of geoelectric strike in the southern part of the Wayang Windu geothermal field using magnetotellurics (MT) data. The strike direction was obtained by analyzing data using impedance polar and Zstrike rose diagram. We investigated 51 MT data at different sites of the southern part of the Wayang Windu geothermal field. Determination of geoelectric strike direction is important since the strike is the rotation references in MT data processing. Our findings had pointed out that the geoelectric strike direction in this study area is in accordance with the direction of geological structure and has a good correlation with structures delineated from 3D MT inversion model.

1. Introduction

The magnetotelluric (MT) technique is a passive electromagnetic (EM) technique that involves measuring fluctuations in the natural electric, E, and magnetic, B, fields at the surface of the Earth as a means of determining the subsurface conductivity structure [1]. This is a passive EM method because the fluctuations of EM fields on the Earth’s surface are generated by the fluctuations of EM field in the atmosphere due to the solar wind and lightning activity, and the fluctuations of secondary inductive EM field in the Earth’s layer due to the resistivity variations of rocks. The EM that included electric (E) and magnetic (H) fields is in orthogonal directions at the Earth’s surface [1]. Therefore, the MT data included two electric \( E_x, E_y \) and two magnetic \( H_x, H_y \) components, both in horizontal layouts with the north-south and east-west directions, and one vertical magnetic \( H_z \) component [2].

The MT method is the most common geophysical method used in geothermal exploration for mapping the resistivity structure below the surface. It is a powerful method to delineate a conductive layer (clay cap) that indicates the existence of geothermal system in the survey area. Moreover, MT method also can delineate geoelectric strike, the difference in lateral resistivity structure. The existence and directions of the geoelectric strike can be delineated by analyzing the already existing information in MT data: impedance polar diagram and impedance strike (Zstrike).

Determination of geoelectric strike direction in MT method is valuable to be rotation references in MT data processing. It is supposed to make the 1D inversion model more reliable after rotation applied at a certain angle depending on the direction of the geoelectric structure near the MT site. In
the other hand, the interpreted geoelectric strike should correlate with 3D inversion model layer to increase our confidence in the interpretation of reservoir zone and reservoir boundary.

In this study, we analyzed the impedance polar diagram and Zstrike rose diagram of MT data in southern part of the Wayang Windu geothermal field. We investigated the 51 MT data at different sites in order to determine the main direction of geoelectric strike in this area. We also made a MT forward modeling as a reference to understand the pattern of impedance polar diagram from the synthetic data to be compared with the real data.

2. Overview of Wayang Windu geothermal field

The Wayang Windu geothermal field is located approximately 40 km south of Bandung, Jawa Barat, Indonesia. The field is surrounded by high topography geothermal systems such as the Kamojang, Darajat, Patuha, Salak and Karaha Bodas fields. It is interpreted to be in transitional between vapour-dominated and liquid-dominated system [3]. It is high-enthalpy geothermal system, with reservoir temperatures above 225 °C. It has operated since 2000 with total installed capacity currently at 227 MWe from unit I and unit II [4]. Currently, it is included in the work area of Star Energy Geothermal Wayang Windu Ltd.

In this study, we define Wayang Windu geothermal field in two zones: the northern and southern field. The northern field is interpreted to be more vapor-dominated system while the southern field is more liquid-dominated system [3]. In this study, we focus only on the southern field to analyze the impedance polar diagram and Zstrike rose diagram to understand the main direction of geoelectric strike.

2.1. Geology of the southern field

The Southern Wayang Windu geothermal field is located in an active tectonic zone where major structural faults and fractures are dominated by WNW, NW, and NE trends. The trends are the best result of combination of many methods based on the integration of surface and subsurface data. Figure 1 shows the geological structure at the southern field. It also shows the location of 51 MT sites in the southern part of the Wayang Windu geothermal field which are used in this study.

Figure 1. Geological map of Southern Wayang Windu geothermal field and location of 51 MT sites.
3. Impedance tensor of MT data

The impedance tensor describes the relation between the electric and magnetic fields, where both are frequency dependent equations. It can be given by

\[ E_i(\omega) = Z_{ij}(\omega) * H_j(\omega) \]  

where \( \omega \) is the frequency and \( Z \) is the impedance tensor related to the electrical properties of subsurface materials. Equation 1 may also be formatted in matrix form as

\[
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix} =
\begin{pmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{pmatrix}
\begin{pmatrix}
H_x \\
H_y
\end{pmatrix}
\]  

where \( Z_{xy} \) and \( Z_{yx} \) are the principal or off-diagonal impedances, \( Z_{xx} \) and \( Z_{yy} \) are the diagonal impedances [5, 6].

The elements of the impedance tensor are in general dependent on the measurement directions of \( x \) and \( y \). The impedance can be rotated through an angle \( \theta \) from the positive \( x \)-axis (north) to a new coordinate system according to:

\[
Z'(\omega) = R(\theta)Z(\omega)R(\theta)^T = RZR^T
\]

where \( R(\theta) = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \) is the rotation operator and \( R^T \) is the transpose of \( R \).

\[
E' = Z'H'
\]

and the elements are

\[
Z'_{xx} = Z_{xx}\cos^2 \theta + (Z_{xy} + Z_{yx})\sin \theta \cos \theta + Z_{yy}\sin^2 \theta
\]

\[
Z'_{xy} = Z_{xy}\cos^2 \theta + (Z_{yy} - Z_{xx})\sin \theta \cos \theta - Z_{yx}\sin^2 \theta
\]

\[
Z'_{yx} = Z_{yx}\cos^2 \theta + (Z_{yy} - Z_{xx})\sin \theta \cos \theta - Z_{xy}\sin^2 \theta
\]

\[
Z'_{yy} = Z_{yy}\cos^2 \theta - (Z_{xy} + Z_{yx})\sin \theta \cos \theta + Z_{xx}\sin^2 \theta
\]

The dependence of the impedance tensor upon the direction of the coordinate axes \( x \), \( y \) can be displayed by polar diagrams [7]. Impedance polar plots provide a measure for the MT data dimensionality.

The most common approximation is based on the maximization of the off-diagonal components of the MT tensor or minimization of the diagonal ones [5]. Then, the strike angle equation can be written as

\[
\alpha = \frac{1}{4} \arctan \left( \frac{(Z_{xx} - Z_{yy})(Z_{xy} + Z_{yx})^* + (Z_{xx} + Z_{yy})(Z_{xy} - Z_{yx})}{|Z_{xx} - Z_{yy}|^2 - |Z_{xy} + Z_{yx}|^2} \right)
\]

where \( ^* \) means the complex conjugate. Equation 5 is also known as Swift angle [8] or Zstrike. Zstrike or the Swift angle gives the electrical strike [9] or we called it the geoelectric strike. Note that the solved strike direction from equation 5 contains a 90° ambiguity, because rotation by 90° only exchanges the location of the two principal impedance tensor elements within the tensor [1].
4. Methodology
The study was divided into several stages: forward modeling, analysis and interpretation of impedance polar diagram of Wayang Windu MT data refer to forward modeling result, making Z strike rose diagram to compare with the result of impedance polar diagram analysis and interpretation, and comparing the geoelectric strikes that obtained from the analysis and interpretation with the geological map and 3D inversion model layer.

4.1. Forward modeling
This forward modeling aims to understand the pattern of impedance polar diagrams from a given resistivity structure model. This pattern is used as a reference to be applied to real MT data analysis. The EDI (Electrical Data Interchange) files of synthetic MT data was generated by forward modeling run using WinGLink for a given 3D resistivity structure model. The EDI files were extracted and used to run the impedance polar diagram map. The pattern of impedance polar diagrams was obtained from these maps.

Figure 2. A given 3D resistivity structure model with three different resistivity values.

Figure 3. Map of impedance polar diagrams from forward modelling and position of geoelectric strike (blue line).

Figure 2 shows a given 3D resistivity structure model in forward modelling with three different colors representing the three different resistivity values. This model’s length, width, and depth are 7000 m, 7000 m, and 3000 m, respectively. Figure 3 shows the impedance polar diagrams as a result of a given model. The geoelectric strike (blue line) distinct two different zones of resistivity. The pattern of the impedance polar diagram elongation is parallel to the strike for the MT stations located in more conductive zone, and perpendicular to the strike for the MT stations located in more resistive zone. Therefore, by using impedance polar diagram, not only the direction of the geoelectric strike can be found, but also the location where the impedance strike shows particular direction.

5. Result and discussion
In this study, we used MT data in EDI file format. We analyzed the 51 MT data in southern Wayang Windu geothermal field to determine the geoelectric strike from impedance polar diagrams map (figure 4) and Zstrike rose diagrams map (figure 5).

Figure 4 shows the impedance polar diagrams in the frequency 0.1 Hz of 51 MT data of southern part of the Wayang Windu geothermal field. The blue lines are the geoelectric strike locations as a result of analysis and interpretation. The blue lines drawn on the map between polar diagrams that relatively perpendicular to each other, which referred to the result of forward modeling. Some of the blue lines have North-West (NW) and the others have North-East (NE) direction trends.

Figure 5 shows Zstrike rose diagrams of southern Wayang Windu geothermal field in the frequency greater than 0.1 Hz. Majority of Zstrike rose diagrams display the direction of geoelectric strike in NW and NE which is correlated with the interpretation of the impedance polar diagram. Briefly, by
comparing figure 4 and figure 5, the strike position of the interpretation of the impedance polar diagram is confirmed by the Zstrike rose diagram.

**Figure 4.** Impedance polar diagram map in the frequency 0.1 Hz and the geoelectric strikes (blue line).

**Figure 5.** Zstrike rose diagram map in the frequency greater than 0.1 Hz.

The direction of the geoelectric strike obtained from the polar impedance diagram and the Zstrike rose diagram correlate to the direction of the geological structure as shown in figure 1, i.e. the direction of the geological structure to the NW and NE trends. We interpreted that this is may be caused by the fluid flow mechanism and alteration process within geological structures which make the resistivity differences laterally.

**Figure 6.** 3D inversion model resistivity layer at different elevation and geoelectric strikes (blue line).
(a) 1000 masl. (b) 750 masl. (c) 500 masl. (d) 250 masl. (e) 0 masl. (f) -250 masl.
To compare with the 3D inversion model, the results of the geoelectric strike from the impedance polar diagram confirmed by Zstrike rose diagram were overlaid with 3D inversion model resistivity layer at different elevation (figure 6). Figure 6 (a), (b), (c), (d), (e), and (f) show the correlation between the geoelectric strike with the resistivity layer at elevation 1000 masl, 750 masl, 500 masl, 250 masl, 0 masl, and -250 masl, respectively. At shallow depth, the clay cap obviously covers the geothermal system and therefore, the correlation between the geoelectric strike and the resistivity structure in the reservoir still cannot be observed. From the figures, the reservoir section begins to reveal at a 500 masl elevation (figure 6c). It can be seen that the strikes represent a lateral resistivity difference in the resistivity layer. At some point, several interpretation of geoelectric strikes have no correlation with the model at a deeper depth, indicating that lateral resistivity variations occur only until a certain depth. However, there are several geoelectric strikes that always correlate consistently with the model in the deep elevation, indicating the possibility that these geoelectric strikes are the reservoir boundary that separates the reservoir zone from its surroundings.

6. Conclusions
This study has yielded results that the direction of geoelectric strike in the southern part of the Wayang Windu geothermal field is in the NW and NE trends. These trends correlate to the direction of the major geological structure. The position of the geoelectric strikes also has a good correlation with 3D inversion model resistivity layer. This is expected to assist a further interpretation of the geothermal area delineation.

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References
[1] Simpson F, and Bahr K 2005 Practical magnetotelluric Surveys in Geophysics (Cambridge: Cambridge University Press) 28 325
[2] Telesca L, Lovallo M, Hsu H L and Chen C C 2012 J. Asian Earth Sci. 54 72
[3] Bogie I, Kusumah Y I and Wisnandary M C 2008 Geothermics 37 347
[4] Masri A, Barton C, Hartley L and Ramadhan Y 2015 Proc. Fortyeth Workshop on Geothermal Reservoir Engineering (Stanford: Stanford University)
[5] Vozoff K 1972 Geophysics 37 98
[6] Reddy I K, Rankin D, and Phillips R J 1977 Geophysics Journal of the Royal Astronomical Society 51 313
[7] Berdichevsky M N 1968 Electrical prospecting by the method of magnetotelluric profiling (Moscow: Nedra Publ. House)
[8] Swift C M 1967 A Magnetotelluric investigation of an electrical conductivity anomaly in the South Western United States Doctoral Thesis (Massachusetts: Massachusetts Institute of Technology)
[9] Teklesenbet A 2012 Multidimensional inversion of MT data from alid geothermal area, eritrea; comparison with geological structures and identification of a geothermal reservoir Master Thesis (Reykjavík: University of Iceland)