Solar Power Estimation Using GIS Considering Shadow Effects for Distribution System Planning

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***Abstract*— During the last decades, photovoltaic (PV) panels have been widely installed in Japanese residential areas to achieve clean and renewable energy. This work employs DSM (Digital Surface Model) layers to extract important elevations, such as trees and buildings, in conjunction with assumptions of cloud movement processes from GIS (Geographic Information System) to obtain realistic solar power affected by solar radiation shading on the PV panel.**

With GIS technology, the solar radiation shading effects are combined with distribution system modeling to observe the significant impact of shadows in the overall distribution system. Moreover, this research can facilitate a more effective distribution system planning by evaluating the influence of PV power variations, assuming a large number of installations.

Keywords—Solar Radiation; Photovoltaic; Geographic Information System (GIS); Digital Surface Model (DSM); Distribution System

I. INTRODUCTION

Nowadays, renewable energy plays a significant role in the generation of electricity, answering the demands of consumers, due to environmental pollution and the shortage of fuel. Renewable energy is receiving increased attention because of the increasing global need for sustainable and clean energy. In Japan, the electricity generated from solar panels is contributing to a significant part of the total energy consumed in many households. Consequently, more panels have been progressively installed. In some areas solar panel installation is not suitable due to obstructions such as shadow casting buildings and trees [1]. To choose an appropriate location there are many methods, for example, using a pyranometer, a measurement system for solar radiation, and calculating the correspondent solar power output from a solar panel. A pyranometer is adequate for a few solar panels but not suitable for wide-area installation. Hence, the Geographic Information System (GIS) program is widely used to estimate solar irradiation on rooftops [2] [3]. After measuring solar radiation, we can predict solar power or solar potential [4] [5].

However, solar power generation from panels is not only affected by the shadows of buildings and trees, but also from the clouds [6]. As the panels are connected to a utility grid, there is a direct impact on the power distribution system [7]. The shadows of the clouds, buildings, and trees have an important impact on distribution systems such as fluctuations of voltage along with the frequency [8] [9]. For this reason, the Spatial Analysis function and DSM (Digital Surface Model) layer from the GIS program, which precisely capture the elevations of the surrounding area, together with assumed cloud movement, were employed for solar power estimation from solar radiation onto the rooftops of an existing residential area located in Kitakyushu City named Jono Area [10]. A model of the distribution system was created based on geographic information.

This research investigated the compatibility of estimated solar power data from the ArcGIS program with the distribution system model including PV installation. Natural phenomena are accounted for by considering the impact of shadows of surrounding objects, such as buildings and trees. Concretely, the effect of the cloud's movement process to the voltage fluctuations in the system was investigated. The aim was to develop concepts for future planning of new residential areas in case that up to every households has solar panels installed.

II. GIS TECHNOLOGY AND APPLICATION

A. Geographic Information System (GIS)

GIS is a technology for creating, gathering, managing, representing, searching, analyzing, and sharing of geospatial information by using a framework. The capabilities of the GIS program are numerous. Therefore, in this paper only the functions relevant for the application in this research are covered. Fig. 1 shows the GIS program managing data by layers, each of which consists of specific geospatial data and an illustration of the real world.

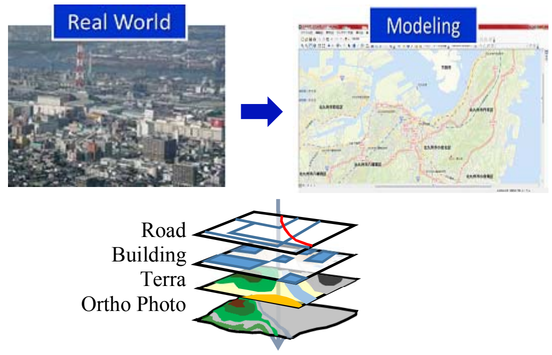

Fig. 1. The principle model of the GIS program

GIS program consists of two essential parts, geospatial data, and program functions. Geospatial data is divided into vector and raster data models. The vector data model consists of layers, using points, lines, and polygons to store boundaries of country borders or streets, while the raster data model encompasses a matrix of pixels organized into grids. Digital aerial photographs, which are taken by a flying object such as a small aircraft or drone, are raster data. The other raster data includes, among others, temperature, altitude and spectrum data. The geospatial data consists of a Digital Surface Model

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(DSM), Digital Elevation Model (DEM), and the road network represented, as shown in Fig. 2. Fig. 3 shows the difference between DSM and DEM layers. DSM contains elevation data from surrounding areas such as trees and buildings, while DEM is representing the ground surface [11].

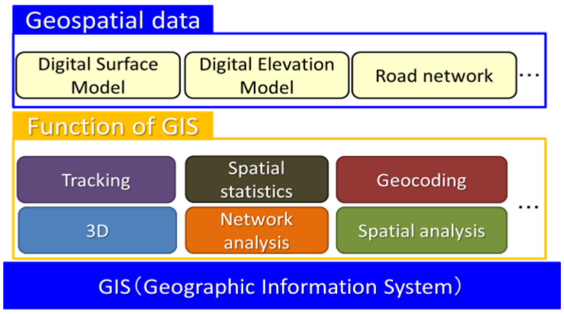

Fig. 2. Geospatial data and function of GIS

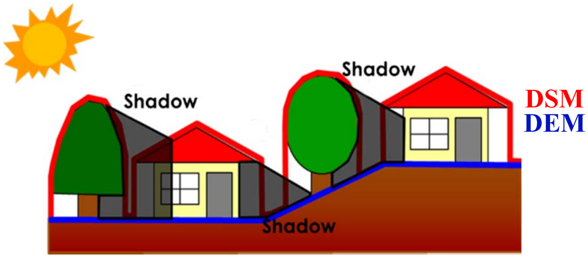

Fig. 3. Illustration of DSM and DEM layers

To create the DSM layer of Jono for this work, Aerial Photograph, which was taken by a drone above Jono residential area, was applied to the program to create a map and determine the distance or elevation from the ratio between the map and the terrain. The Spatial Analysis function was employed simultaneously with a real-world map to determine the height of trees and buildings that are the causes of shadows, as shown in Fig. 4. Fig. 5 shows the elevation map or DSM layer of Jono. The dark color to bright color gradient represents the different elevation inside the area. The brightest color or white-grey color shows the highest buildings in the area. The darker the color is, theheight of buildings or surrounding objects is lower.

To make use of raster and vector data models, the spatial analyst toolbox was employed to create a solar radiation map in the interest area at a specific time. Area Solar Radiation functions were used to create a solar radiation map. The Area Solar Radiation tools can derive incoming solar radiation from a raster surface. The Spatial Analyst tool which works together with the solar radiation map technique is demonstrated further in the following section.

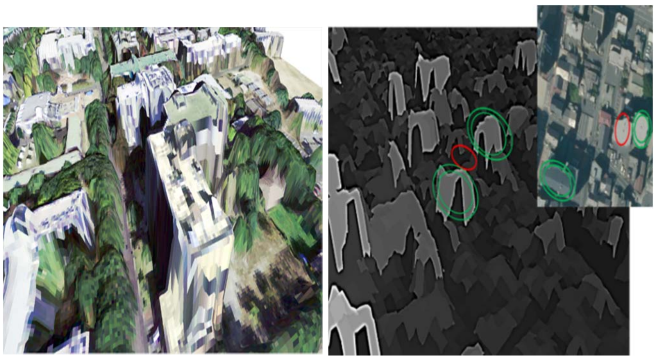

Fig. 4. Illustration of aerial photograph overlaps with DSM layer in 3D

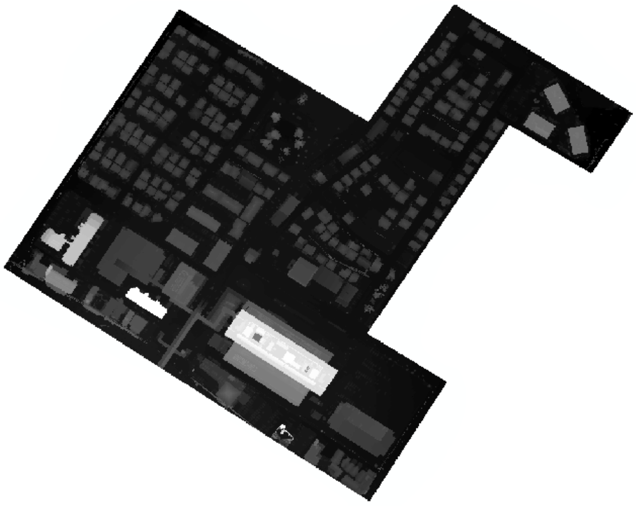

Fig. 5. DSM layer of Jono area

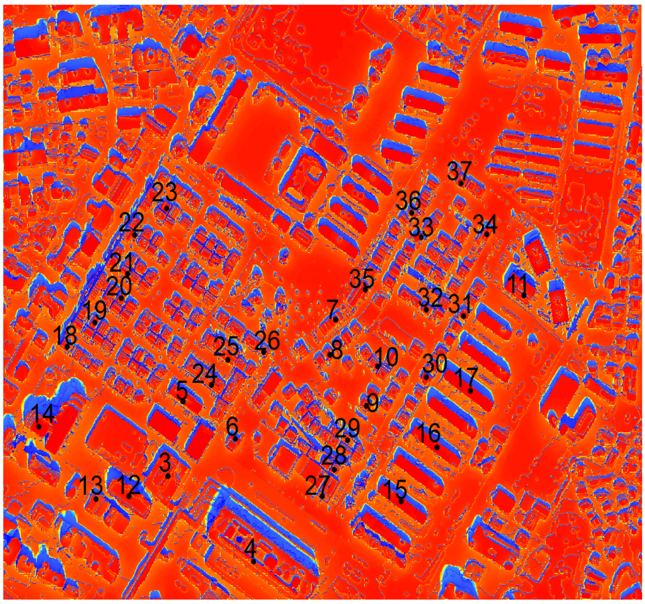

Fig. 6. Defined bus on Jono solar radiation map

B. Solar Radiation Map

Solar radiation or solar irradiation is the light emitted from the sun that is incident on surface of the Earth in a magnetic waveform. This is relevant for the present work, because it is the power source used by solar panels to generate electricity. This research focuses on the effects of reduced solar radiation due to partial or total covering of the PV panels with shadows from buildings, trees, and clouds.

With the Area Solar Radiation function from the solar radiation analysis toolboxes in the GIS program it is possible to calculate solar radiation maps using the DSM layers. To represent the solar radiation map, this research employed DSM layer and area solar radiation map function working with orbital data of the sun in a specific area using an explicit aerial photograph to extract the shadow of the entire area.
In this work, after the Jono DSM layer was created, the solar radiation map, or Jono solar radiation map (Fig. 6), was calculated, assuming clear weather conditions (sunny day) to obtain the solar radiation value in each bus point of the distribution system. From the GIS program, the loading-point affiliated with Jono residential area can be defined, as shown

in Fig. 6. This research focuses on the effects of reduced solar radiation due to partial or total covering of the PV panels with shadows from buildings, trees, and clouds. These concepts are expanded in the following sections.

III. Power Distribution System

Fig. 7 shows the modified distribution system model of this work representing the real-world area of Jono, in Kitakyushu City. Jono Area, also known as Smart Community Area with high penetration of solar panel installation is shown in Fig. 8. The distribution model was modified in order to consider the effect of shadows that cover the solar panels in the residential section of the system. It is assumed that there are 350 households in the Jono residential areas (10 houses per bus). In every bus the PV installation rate is about 50% of the connected households.

This work defined loading-points from bus 3 to bus 37 (35 buses) according to the residential area in the Jono solar radiation map, as shown in Fig. 6. Fig. 8 shows the defined buses area of bus 22, 23 and 33 as a real-world map. Buses were defined by pinning the bus points on the solar panels' locations for obtaining solar radiation values from the solar radiation map in order to predict the accurate solar power for each panel. This data was then applied to the distribution system model in MATLAB/Simulink, named Jono distribution model.

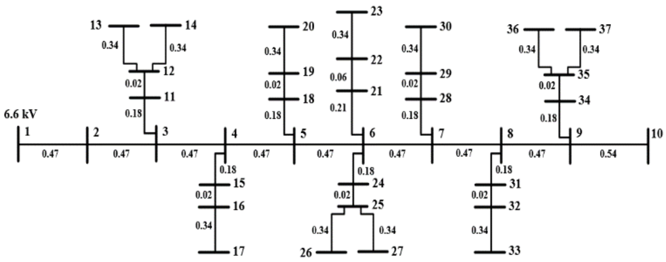

Fig. 7. The distribution system model and defined bus point

Fig. 8. Smart community, Jono

IV. Proposed Methology

This section covers the methodology of capturing the cloud's movement process and the application of the solar radiation map to the distribution system. From the GIS program, the solar radiation map can be created for a specified day and time, taking into consideration the weather conditions. In this work, it is crucial to be able to obtain solar radiation data in the case that clouds cover high percentage solar panel installation areas, because of the direct impact on the distribution system. For this reason, we contrived the cloud's movement process and applied it to the solar radiation map to identify the decrease of the solar irradiation value due to shadows from the cloud. Fig. 8 shows the comparison between real-world map and solar radiation map of residential bus number 37. This bus was defined according to the Jono distribution model by pinning it on the rooftop where the solar panel is located. After obtaining solar irradiance data, the solar power from the defined buses area was estimated. Then, the compatibility with the MATLAB/Simulink model of the Jono distribution system for analyzing the impact of shadows by clouds, buildings and trees to voltage fluctuation in the distribution system was investigated.

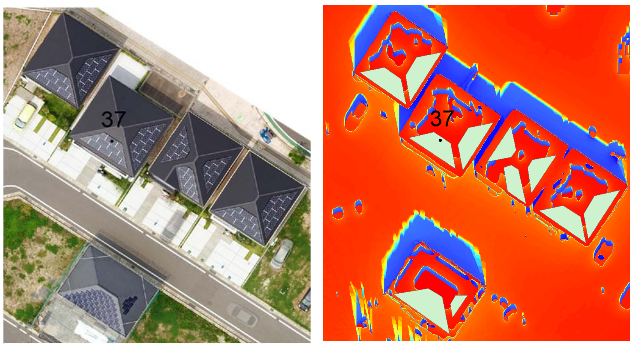

Fig. 9. The comparison between real-world and solar radiation map of residentials bus number 37

A. *Cloud's Movement Process*

The solar irradiation values can be readily determined from the GIS program and the Jono DSM layer. However, this solar radiation map extracts only the shading effect from buildings and trees. Thus, the shadow on a cloud covered area that decreases the solar radiation by 60.56% had to be determined. The radiation decrease is due to the discrepancy of the transparency between a cloudy day and a sunny day calculation from the GIS program on the example day, 19th September 2019 from 12:00 to 12:30. Fig. 10-a and 10-b show the assumed cloud's movement, supposing that a cloud passed over the Jono area in southwest direction during a one-minute period to study the impact from the cloud to the distribution system. From the GIS program, sixty pictures of the cloud were applied (one picture per second for 60 seconds) to the Jono solar radiation map.

This research assumed the beginning of the cloud's movement into the area to be at 7 seconds in the simulation. It moves out again from area at 59 seconds. The solar radiation of the bus areas that were covered by the shadow from the cloud was decreased, therefore it is possible to predict the generated solar power from PV panel from the defined buses. The reduction of solar radiation in the area when covered by the cloud was represented by a color change from dark orange or orange to yellow. The area that is covered by buildings, trees or other surrounding objects is represented by a color change to blue or dark blue as shown in Fig. 9.

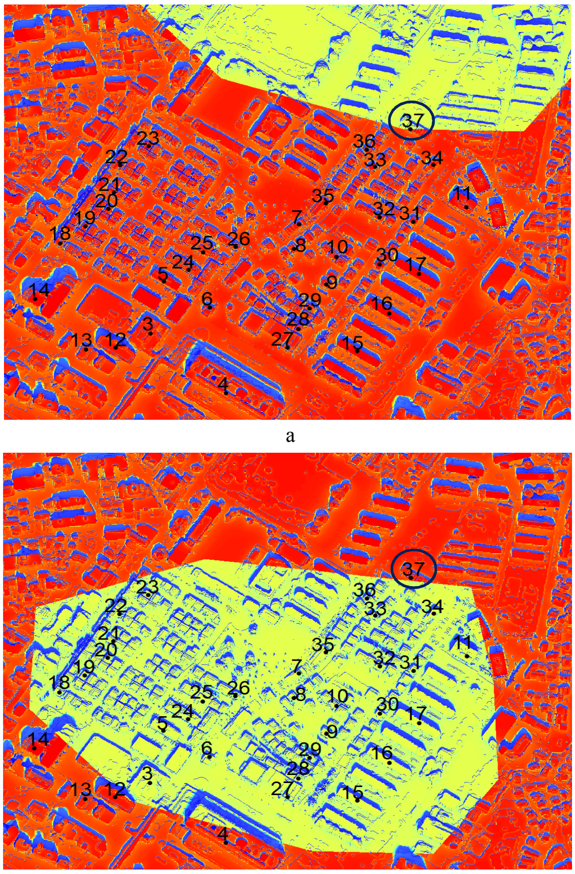

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Fig. 10. Cloud's movement process

In order to map the cloud's movement process, spatial analyst tools and related functions were employed to create a cloud in the solar radiation map and the movement process to study the impact of shadows of clouds on real-world residential areas. Sixty pictures of the cloud per second were combined to create the cloud's movement path by feature class function. The clip function was used to combine a cloud's picture and the solar radiation map on the same layer. Then, the times function was applied to define the transparency. This research assumed 60.56% of solar radiation to be cut by the cloud's layer. Finally, the mosaic to new raster function was employed to combine the cloud's layer with the solar radiation map.

B. *Calculating PV power generation using solar radiation map*

Initially, 30 minutes (12:00-12:30, date 2019/09/19) of the solar radiation map were simulated on sunny day conditions with the effect of shadows from clouds, buildings, and trees. In this sequence, the solar radiation values (Wh/m^2) were collected from a defined bus on the map. For example, Fig. 8 shows the defined residential bus number 37. From the ArcGIS program the solar radiation value at bus number 37 can be collected for a specific period. The area solar radiation function calculates the solar radiation map every 30 minutes. This means the solar radiation value is integrated over a period of 30 minutes. For example, for a value of 311.34 Wh/m^2 (solar panel at rooftop position, blue or dark blue color, indicating the shadow covered areas) the solar radiation decreased to 14.40 Wh/m^2. The solar radiation unit was transformed to kW/m^2 for compatibility with the Jono- distribution model from MATLAB/Simulink. The transformation formula is given by the following equation:

$$\text{kW/m}^2 = \text{Solar Radiation (Wh/m}^2\text{)/(1000)(0.5 h)} \qquad (1)$$

Solar radiation values have been collected in each bus point from the solar radiation map in Wh/m^2. The value of 0.5 in the above formula corresponds to half an hour (30 minutes) of the solar radiation map simulation. At bus number 37 from Fig. 9, the solar power was transformed to kW/m^2. The resulting value is 0.623 kW/m^2 while the value in the shadow covered area (blue color area) is 0.0288 kW/m^2. To transform kW/m^2 to kW, the MATLAB/Simulink program was used to transform the value to kW. The resulting values were then used for the simulate of the Jono distribution system. The transforming equation used in MATLAB/Simulink is given as follows:

$$\text{AC PV Power} = \text{(kW/m}^2\text{)(area)(efficiency)} \qquad (2)$$

The formula uses the solar radiation value in kW/m^2 and the average area of PV panels from the residential zone. This research assumed a panel's area to be 25 m^2 by averaging the size of a solar rooftop. To obtain the size of panels, the panels from the Aerial Photograph of Jono area were measured using the GIS program. The total solar rooftop size on each household varies between 10 m^2 to 30 m^2. For this reason, the area of panels was estimated. The efficiency of system is 0.85. The kW unit value is the input to the distribution system in the MATLAB/Simulink to find the impact from shadows of clouds, buildings, and trees to the voltage fluctuation in the Jono distribution system.

V. Simulation and Results Analysis

The simulation was done employing the solar radiation map and the cloud's movement process on 19th September 2019 12:00-12:30 pm. The cloud started to cover the Jono area at 7 seconds from bus 37, as shown in Fig. 10-a. At 8 seconds the cloud moved to bus 36 and left from bus 4 at 59 seconds in southwest direction. To represent the impact from shadows of neighboring areas such as clouds, buildings, and trees, the solar power from defined buses was applied, which is affected by the cloud's movement process from the solar radiation map and has impact on the distribution system. This way it was possible to examine the voltage fluctuation in high percentage installation of solar panels in a residential area system. The simulation analysis part interprets results with voltage fluctuation graphs on the low voltage side (~105 V), meaning the voltage in the households area in the defined buses located on the solar panels, and the high voltage side (~6.6 kV), meaning the voltage between the distribution buses, as shown in Fig. 12-a and 12-b.

Fig. 12-a and 12-b show the simulation results after the solar radiation values (in kW/m^2 unit) were considered, with the added effects of the cloud's movement to the input of the Jono distribution system model. The graph of Fig. 12-a shows the low voltage side (around 105 V) of each consumer's household in the residential area. Fig. 12-b shows the high voltage side (around 6.6 kV) between the distribution bus points. Both sides have voltage fluctuation following the shadow from the cloud in Fig. 10-a. For example, between 7 and 33 seconds, it was assumed that a cloud moved into Jono area. Its shadow was defined to be covering bus 37 (blue line in the graph). The bus location is shown in Fig. 11. For this reason, the line in the graph shows the voltage drop from the 7 to the 33 seconds, during which time the cloud passed over

bus point 37. The voltage then returned to its original value. Fig. 12-b shows the influences of the voltage fluctuation in the residential area side to the overall system. For example, at 7 seconds, the cloud covered defined bus 37 made the voltage in the connected buses from the model (bus 8, 9, 10, 31, 32, 33, 34, 35, 36, and 37) drop, following the shadow of a cloud. However, the others buses (such as the main buses of, 7, 8, 9, and 10) show voltage variation owing to the cloud in descending order, because of their respective distances from the bus 37 and beside buses. In this way, those buses sustain influence from the voltage drop in wide area close to bus 37 as shown in Fig. 11. Further, the main buses are located near an existing generator or slack bus. For example, in the graph 12-b, bus 3 (yellow line), bus 4 (brown line), bus 5 (grey line), and bus 6 (turquois line) the voltage deviation increases because the voltage fluctuations from solar panels that are installed in prevalent rate in every bus of Jono residential areas and slack bus in the distribution system are compensated. The buses in the 6.6 kV (distribution side) area are directly connected to each other, leading to the ability to support each other's voltages. On the other hand, the 105 V area (households' side) buses are independent because the households at difference distribution buses are not connected to each other on the low voltage side. They simply connect to the 6.6 kV bus through a feeder.

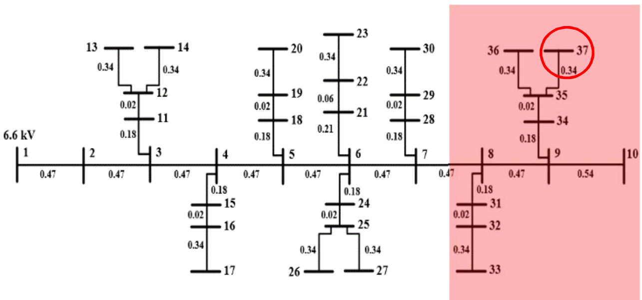
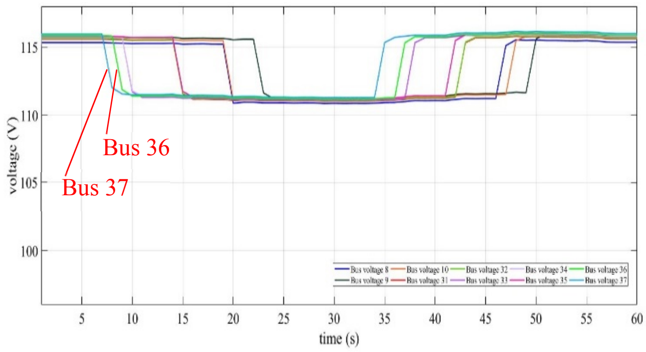


Fig. 11. The affected from cloud to distribution system



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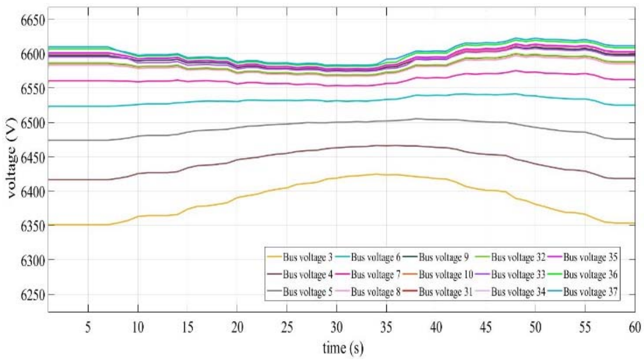

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Fig. 12. Voltage fluctuation graphs

VI. Conclusions

The results in this paper showed the effects from the shadows in the Jono distribution system with high percentage installed solar panels, caused by a cloud's movement into a residential area. The system was affected by shade from the cloud's movement process, along with the shadows from trees and buildings, leading to a decrease in the solar radiation values. For this reason, total solar power (kW) was also reduced, affecting the distribution system.

This paper shows merits of GIS program functions and the application of the program for working together with Digital Surface Model (DSM layer) to extract the solar radiation map in a specific place, date and time. Moreover, the data from GIS can be applied to a distribution system model. This way it is possible to study the impact of decreased solar power to the system, such as frequency deviations. In case of a high penetration of solar power systems, estimation of the solar power from solar panels for responding to the demand of consumers is necessary. In the future, the percentage of installed PV in households in distribution systems will increase. It is important to perform a thorough distribution system planning previous to the residential areas' construction.

References

[1] Y. Choi, J. Suh, and S. M. Kim, "GIS-based solar radiation mapping, site evaluation, and potential assessment: A review," *Appl. Sci.*, vol. 9, no. 9, 2019.

[2] D. Li, G. Liu, and S. Liao, "Solar potential in urban residential buildings," Sol. Energy, vol. 111, no. May 2018, pp. 225–235, 2015.

[3] P. Mavsar, K. Sredenšek, B. Štumberger, M. Hadžiselimović, and S. Seme, "Simplified method for analyzing the availability of rooftop photovoltaic potential," Energies, vol. 12, no. 22, 2019.

[4] M. Brumen, N. Lukač, and B. Žalik, "GIS Application for Solar Potential Estimation on Buildings Roofs," … Build. Explor. Web Based …, vol. Brumen, M., no. c, pp. 1–6, 2014.

[5] J. Ordóñez, E. Jadraque, J. Alegre, and G. Martínez, "Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia(Spain)," Renew. Sustain. Energy Rev., vol. 14, no. 7, pp. 2122–2130, 2010.

[6] C. Cai and D. C. Aliprantis, "Cumulus cloud shadow model for analysis of power systems with photovoltaics," IEEE Trans. Power Syst., vol. 28, no. 4, pp. 4496–4506, 2013.

[7] Y. Kakumoto, Y. Koyamatsu, A. Shiota, Y. Qudaih, and Y. Mitani, "Application of Geographic Information System to Power Distribution System Analysis," Energy Procedia, vol. 100, no. September, pp. 360–365, 2016.

[8] W. Shen and Y. Zhu, "Impacts of small photovoltaic power station on voltage sag in low-voltage distribution network," 2011 Int. Conf. Electr. Control Eng. ICECE 2011 - Proc., pp. 1585–1588, 2011.

[9] R. Darussalam and I. Garniwa, "The effect of photovoltaic penetration on frequency response of distribution system," Proc. - 6th Int. Conf. Sustain. Energy Eng. Appl. ICSEEA 2018, pp. 81–85, 2019.

[10] M. Howlader, M. Howlader, S. A. Khan, A. U. Nur, and A. Amin, "GIS- Based Solar Irradiation Forecasting Using Support Vector Regression and Investigations of Technical Constraints for PV Deployment in Bangladesh," pp. 675–680, 2017.

[11] A. Shiota, Y. Koyamatsu, K. Fuji, Y. Mitani, and Y. Qudaih, "Development and Public Release of Solar Radiation Map for Effective Use of Solar Energy Based on GIS with Digital Surface Model," Int. J. Electr. Energy, vol. 3, no. 3, pp. 169–1 Electr. Energy, vol. 3, no. 3, pp. 169–173, 2016. Use of Solar Energy Based on GIS with Digital Surface Model," Int. J. Electr. Energy, vol. 3, no. 3, pp. 169–173, 2016.