Solar Road Power Generation Assessment Based on Coupled Transportation and Power Distribution Systems

Lingjie Wu*, Yue Yuan and Han Wu

College of Energy and Electrical Engineering, Hohai University

*ljwu18@hhu.edu.cn

Abstract. The rising of energy demand together with environmental protection awareness have attracted worldwide interest in renewable energy, especially photovoltaic (PV). Meanwhile, with the expansion of transportation infrastructure, solar energy has been employed in roadway construction, called solar road. The technology of Solar road offers an opportunity to capture the vast and dispersed solar energy while maximizing the use of land. A PV power generation assessment method for solar road considering coupled distribution and transportation system is proposed in this paper. The dynamic shading caused by traffic flow on solar road is considered as an effect factor which will influence the PV output in the model. The proposed method is examined on a test system with a transportation and a radial distribution network. The numerical results substantiate that the proposed method is an effective tool for assessing the PV power generation of solar road.

1. Introduction

Distribution generation, especially photovoltaic energy (PV) has aroused great attention due to its attractive properties such as low cost and nearly free-pollution over the last decade. However, generating energy from solar irradiation is subject to the geographical constraint due to its dispersion. The transportation network contains a lot of solar energy, it is possible to maximize the utilization of both lands and insolation resources by capturing PV energy from roadways [1].

Thus, the solar road technology was proposed to convert PV resources on vast of land into electricity. Although the solar road technology is still in its infancy, a great potential is seen for solar road application with the maturity of the PV technology. Besides, A vision of sustainable roadways with solar road and wireless transmission for developing an intelligent transportation system is presented in [2].

At present, the United States, the Netherlands, France, China and other countries have carried out research on solar roads. The U.S. solar road study began in 2006 and was finally completed in 2014, applying solar roads on community roads. In 2014, the Netherlands successfully built a 70-meter-long, 2-meter-wide solar bike path in the northern city of Krommenie. In 2016, the first solar road in France was completed in the Normandy province, the road is about 1 km long and 2 meters wide. This section of the road generates an average of nearly 800 kWh of a day, about 280,000 kWh a year, enough to power the daily public lighting of a town of 5,000 people. Based on this research, France plans to build a total of 1,000 km of solar roads across the country in the next five years. China’s first solar road completed in 2017 in Jinan, Shandong province (about 1.1 km). There are electromagnetic induction coils under the road surface, which can realize wireless charging of electric vehicles during driving.
A power generation assessment method for solar road with the consideration of coupled transportation and distribution network system is proposed in this paper. To examine the proposed method, a test system with transportation network and radial distribution network structure is employed in the case study.

2. Analysis of PV output of solar road

The power output of solar road is subject to the operating temperature and efficiency. Both of temperature and efficiency are described as below. Take the solar path in Krommenie for sample, consisting of 270Wp PV modules. Based on these, the power output can be calculated. Besides, the dynamic shading caused by moving vehicles is also considered.

2.1 Solar Road Operating temperature

The operating module temperature described in [3] is iteratively computed as below

$$T_M = \frac{\varphi G_M + h_c T_a + h_{con} T_g + h_{r,sky} T_{sky} + h_{r,gnd} T_g}{h_c + h_{con} + h_{r,sky} + h_{r,gnd}}$$

in which $\varphi$ is the absorption of solar road, $G_M$ represents the irradiance, $T_M, T_a, T_g, T_{sky}$ are the temperature of module, ambient, ground and sky respectively. $h_{r,sky}$ represents the radiative heat coefficient between the sky and top surface. $h_{r,gnd}$ represents the radiative heat coefficient between the ground and bottom surface.

2.2 Solar Road Operating efficiency

The module temperature and the irradiance determine the efficiency [3]. The temperature dependant efficiency is determined by (2).

$$\eta(T_M, G_{stc}) = \frac{P_{max}(T_M, G_{stc})}{A_M G_{stc}}$$

in which $P_{max}(T_M, G_{stc})$ represents the maximum module output at temperature $(T_M)$ and irradiance $(G_{stc})$. $P_{max, stc}$ represents the standard maximum output. $A_M$ represents the module area.

The irradiance dependant efficiency can be determined by (3).

$$V_{oc}(T_{stc}, G_M) = V_{oc, stc} \frac{\ln G_M}{\ln G_{stc}}$$

$$I_{sc}(T_{stc}, G_M) = I_{sc, stc} \frac{G_M}{G_{stc}}$$

$$P_{max}(T_{stc}, G_M) = FF \cdot V_{oc}(T_{stc}, G_M) \cdot I_{sc}(T_{stc}, G_M)$$

$$\eta(T_{stc}, G_M) = \frac{P_{max}(T_{stc}, G_M)}{A_M G_{stc}}$$

where $V_{oc}(T_{stc}, G_M)$ represents the open circuit voltage. $I_{sc}(T_{stc}, G_M)$ is the short circuit current. $FF$ represents the module fill factor.

The cumulative effect of temperature and irradiance change on module efficiency can be computed by (4).
where \( \eta(T_M, G_M) \) is the operating efficiency of PV module, together with the irradiance, the PV output on solar road can be determined.

2.3 Power output considering dynamic shading

The power output of solar road is also subject to static and dynamic shading. The static shading caused by structures and trees is considered in [4]. However, the effect of dynamic shading causing by moving wheels was not considered. Thus, in this paper, the influence of wheels is considered by the transportation network model. The actual output of solar road is proposed as follow

\[
P_{\text{actual,}t} = P_{\text{road,}t} \left[ 1 - \frac{\text{Num}_{\text{vehicle}} \cdot S_{\text{vehicle}}}{S_{\text{road}}} \right]
\]  

in which \( P_{\text{road,}t} \) is the estimated output of solar road without considering dynamic shading, \( \text{Num}_{\text{vehicle}} \) is the number of vehicles moving above the road at that moment, \( S_{\text{vehicle}} \) is the shading area of each vehicle and \( S_{\text{road}} \) is the total area of the solar road.

3. Coupled Transportation and distribution system model

3.1. Transportation network model

3.1.1. Assumptions. In order to facilitate the mathematical model, some assumptions are proposed as follow.

1) Since most of the trips within the city are less than 50km, we assume that all vehicles have enough fuel to cover all distances.

2) All vehicles have the same shading area of irradiance.

3.1.2. Multi-path traffic flow assignment model. Traffic flow assignment refers to the distribution of space origin to destination (O-D) quantity to the transportation network and obtain the traffic flow of links respectively.

In order to describe the function relationship between the travel time and the traffic load of road sections, the most widely used one is suggested by the Bureau of Public Roads (BPR) and given by [5]

\[
t_a = t_a^0 \left[ 1 + 0.15 \left( \frac{x_a}{c_a} \right)^4 \right], \forall a \in T_a
\]  

where \( t_a^0 \) represents the free travel time, i.e., \( x_a \) is traffic flow on link \( a \), and \( c_a \) is called the link capacity.

The right-of-way (driving time between sections) is the sum of passing time of the road and the delay of the intersection

\[
T(i, j) = t(i, j) + d(i, j)
\]  

in which \( t(i, j) \) and \( d(i, j) \) represent the driving time and the delay time respectively.
The feasible link is an important concept in traffic flow assignment, while the traditional definition would make some of the feasible links not to assign traffic flow. Thus, the relative error is introduced to redefine the feasible links

\[
\frac{L_{\min}(r,i) + d_{\min}(i,s-r) - L_{\min}(r,s)}{L_{\min}(r,s)} \quad (8)
\]

where \(L_{\min}(r,i)\) represents the minimal road resistant between origin \(r\) to node \(i\), \(d_{\min}(i,s-r)\) represents the minimal road resistant between node \(i\) and destination \(s\), and \(L_{\min}(r,s)\) is the minimal resistant between the origin and the destination.

According to the above, if the right-of-way between the selected path and the shortest path is less than \(\theta\), this path \(r-s\) is called the feasible path

\[
L_{\min}(r,i) + d_{\min}(i,s-r) \leq (1 + \theta)L_{\min}(r,s) \quad (9)
\]

when node \(r\) and \(i\) satisfy the function above, link \(r-s\) is the feasible link.

After that, the Logit probabilistic path selection model can be used to calculate the assignment rate on each path

\[
P_{rs}^k = \frac{\exp(-\sigma t_{rs}^k / \bar{T}_{rs})}{\sum_{j=1}^{m} \exp(-\sigma t_{rs}^j / \bar{T}_{rs})} \quad (10)
\]

\(\sigma\) is assignment parament, \(t_{rs}^k\) is the right-of-way of the path \(k\), \(\bar{T}_{rs}\) is the average right-of-way of each feasible path, \(m\) is the number of the feasible paths.

Multi-paths traffic flow assignment process is shown as below

**Figure 1.** Process of multi-paths traffic flow assignment.

### 3.2 Distribution network model

**3.2.1 Objective function.** In the model, the power generation of solar road will be the objective

\[
f = \sum_{i \in \Psi_{road}} P_{i,t}^{road} \Delta t \quad (11)
\]

in which \(\Psi_{road}\) represents the set of the nodes connected to solar roads, \(P_{i,t}^{road}\) is the active PV output at bus \(i\) for installing solar road in different times.
3.2.2 Constraints

(1) PV output constraints

\[
\begin{align*}
0 \leq P_{\text{road}}^{i,t} & \leq P_{\text{E}}^{i,t} \\
Q_{\text{road}}^{i,t} & = \tan \varphi_i \cdot P_{\text{road}}^{i,t} \\
\forall i & \in \Psi_{\text{road}}
\end{align*}
\]  

Equation (12) represents the PV output constraints. Where \( P_{\text{E}}^{i,t} \) represents the expected output of PV at bus \( i \) of different times. \( \varphi_i \) is the power factor angle.

(2) Power flow constraints

\[
\begin{align*}
\sum_{ij \in \Phi_b} p_{ij,t} & = P_{\text{road}}^{i,t} - P_{\text{L}}^{i,t} \\
\sum_{ij \in \Phi_b} q_{ij,t} & = Q_{\text{road}}^{i,t} - Q_{\text{L}}^{i,t} \\
\forall i & \in \Psi_n
\end{align*}
\]  

Equations (13) represents the active and reactive power injection at each bus in the distribution system, where \( p_{ij,t}, q_{ij,t} \) represent the active and reactive power flow of branch \( i,j \). \( P_{\text{L}}^{i,t}, Q_{\text{L}}^{i,t} \) are the active and reactive load demand at bus \( i \) in time \( t \), respectively. \( \Psi_n \) denotes the set of all buses.

(3) Branch thermal constraints

\[
\begin{align*}
U_{i,t} & = (V_{i,t})^2 \quad \forall i \in \Psi_n \\
V_{i,t}^2 & \leq U_{i,t} \leq \overline{V}_i^2 \quad \forall i \in \Psi_n \\
U_{i,t} - U_{j,t} & = 2(r_{ij} \cdot p_{ij,t} + x_{ij} \cdot q_{ij,t}) - (x_{ij}^2 + r_{ij}^2) \cdot \frac{p_{ij,t}^2 + q_{ij,t}^2}{U_{i,t}} \quad \forall ij \in \Phi_b
\end{align*}
\]  

Equations (14)-(15) are bus voltage constraints, where \( V_{i,t} \) and \( U_{i,t} \) represent the bus voltage and its square. Besides, Equation (16) is the Distflow power flow, in which \( \Phi_b \) represents all branch sets, \( r_{ij} \) and \( x_{ij} \) represent resistance and reactance.

(4) Power balance constraints

\[
\begin{align*}
\sqrt{p_{ij,t}^2 + q_{ij,t}^2} & \leq S_{ij}^{\text{max}} \\
\forall ij & \in \Phi_b
\end{align*}
\]  

Where \( S_{ij}^{\text{max}} \) represents the maximum apparent power of branch \( i,j \).

4. Case study

4.1 Basic settings

The power generation results on a test system with a transportation network and a radial distribution network is shown in this section. The topology of the transportation network is shown in figure 2, consists of twenty solar roads (SR). The length of SR2, SR5, SR16 and SR19 are 400\( \sqrt{2} \) meters and the width of them are 8 meters. The length and width of the others are 400 meters and 8 meters. The power distribution network topology is shown in figure 3. It is a 12-bus radial network and each node is connected to one or more solar road.
Figure 2. Topology of transportation system.

Figure 3. Topology of the power distribution system.

4.2 Results
In [6], authors estimated the power output of solar road at Krommenie, using the irradiance data for every hour of the year 2015. However, the dynamic shading caused by moving vehicles was not been considered. Here, the irradiance data of a typical day is used to test our proposed method, the estimated power output of SR1 in the testing transportation network is shown in figure 4.

Figure 4. Estimated power output of SR1.
In order to evaluate the impact of moving vehicles adequately, four different cases are tested for comparison. We assume that 10000/20000/50000 vehicles have travelled from 7 a.m. to 19 p.m. in this transportation network system. Besides, the case which not considering traffic flow is also been tested for comparison. Table 1 shows the O-D pairs and their traffic demands. The multi-paths traffic flow assignment method is applied to compute the traffic flow. The traffic flow of 10000 vehicles is shown in figure 5 as a sample. In order to make the result more reasonable, we allocate the flow to time periods according to real time-varying characteristic of traffic flow. For example, peak traffic is around 9 a.m. and 5 p.m.

Table 1. OD pairs and trip rate.

| O-D pair | Rate (%) | O-D pair | Rate (%) |
|----------|----------|----------|----------|
| T1-T6    | 9        | T3-T6    | 9        |
| T1-T10   | 18       | T3-T10   | 15       |
| T1-T11   | 13       | T3-T11   | 12       |
| T1-T12   | 10       | T3-T12   | 14       |

Figure 5. Traffic flow of 10000 vehicles.

The results of four cases are given in table 2.

Table 2. Power generation of four cases.

| Traffic         | Case 1         | Case 2         | Case 3         | Case 4         |
|-----------------|----------------|----------------|----------------|----------------|
| Not been        | 10000          | 20000          | 50000          |                |
| considered      |                |                |                |                |
| Power Generation (MWh) | 44.748  | 44.176         | 43.616         | 41.939         |

As you can see from table 2 that the power generation of solar roads is overvalued if the traffic flow is not considered. The gap between the cases considering traffic flow increases with the number of vehicles. This is understandable because the dynamic shading caused by moving traffic will reduce the PV output of solar roads and leads to less power generation for whole day. The larger the number of vehicles moving above the solar roads, the lower power generation will be. Thus, traditional method fails to consider the dynamic shading and leads to inaccurate estimation of power generation of solar roads. Moreover, the overvalued result which not considering traffic flow will affect power network
security and dispatching. Therefore, it is important to take traffic flow into consideration when assessing the PV generation of solar roads.

5. Conclusion
A novel PV generation assessment method of solar road based on coupled transportation and power distribution network is proposed. The dynamic shading caused by moving vehicles is considered in the coupled model to quantitative its influence on the energy yield of solar road. Then, a multi-paths traffic flow assignment method is applied to calculate the flow in transportation network. To verify the effectiveness of the proposed method, a coupled system with a transportation and a radial power distribution network is tested. The results showed that the power generation would be more accurate in the cases which considering the traffic flow. In addition, the more traffic is considered, the more significant the impact is.

This work offers an effective framework for power generation assessment problem for solar road and the dynamic shading influence causing by moving vehicles can be quantified. This proposed scheme is able to provide accurate generation to the distribution system planner.

In addition, there are other uncertainty factors may affect the PV output of solar road. There are strong correlations between the outputs of dispersed PV. This correlation of PV output will be researched in the future work.

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