Tamer Khatib | Wilfried Elmenreich

Simplified Green Codes

Modeling of PHOTOVOLTAIC SYSTEMS Using MATLAB®

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MODELING OF PHOTOVOLTAIC SYSTEMS USING MATLAB®

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Tamer is a photovoltaic power systems professional. He holds a B.Sc. degree in electrical power systems from An-Najah National University, Palestine, as well as a M.Sc. and a Ph.D. degrees in photovoltaic power systems from National University of Malaysia, Malaysia. In addition, he holds a habilitation degree in renewable and sustainable energy from the University of Klagenfurt, Austria. Currently he is an assistant professor at Energy Engineering and Environment Department, An-Najah National University, Nablus, Palestine. So far, he has published over 85 published research articles, meanwhile his current h-index is 14. Moreover, he has supervised six Ph.D. and four M.Sc. researches. He is a senior member of IEEE Power and Energy Society and member of the International Solar Energy Society.

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Wilfried Elmenreich studied computer science at the Vienna University of Technology where he received his master's degree in 1998. He became a research and teaching assistant at the Institute of Computer Engineering at Vienna University of Technology in 1999. He received his doctoral degree on the topic of time-triggered sensor fusion in 2002 with distinction. From 1999 to 2007 he was the chief developer of the time-triggered fieldbus protocol TTP/A and the Smart Transducer Interface standard. Elmenreich was a visiting researcher at Vanderbilt University, Nashville, Tennessee, in 2005 and at the CISTER/IPP-HURRAY Research Unit at the Polytechnic Institute of Porto in 2007. By the end of 2007, he moved to the Alpen-Adria-Universität Klagenfurt to become a senior researcher at the Institute of Networked and Embedded Systems. Working in the area of cooperative relaying, he published two patents together. In 2008, he received habilitation in the area of computer engineering from Vienna University of Technology. In winter term 2012/2013 he was professor of complex systems engineering at the University of Passau. Since April 2013, he holds a professorship for Smart Grids at Alpen-Adria-Universität Klagenfurt. His research projects affiliate him also with the Lakeside Labs research cluster in Klagenfurt. He is a member of the senate of the Alpen-Adria-Universität Klagenfurt, senior member of IEEE, and counselor of Klagenfurt's IEEE student branch. In 2012, he organized the international Advent Programming Contest. Wilfried was editor of four books and published over 100 papers in the field of networked and embedded systems.

FOREWORD

Recently, photovoltaic system theory became an important aspect that is considered in educational and technical institutions. Therefore, the theory of photovoltaic systems has been assembled and introduced in a number of elegant books. In the meanwhile, the modeling methodology of these systems must be also given a focus as the simulation of these systems is an essential part of the educational and the technical processes in order to understand the dynamic behavior of these systems. Thus, this book aims to present simplified coded models for these systems' component using Matlab. The choice of Matlab codes stands behind the desire of giving the student or the engineer the ability of modifying system configuration, parameters, and rating freely. This book comes with five chapters covering system's component from the solar source until the end user including energy sources, storage, and power electronic devices. Moreover, common control methodologies applied to these systems are also modeled. In addition to that auxiliary components to these systems such as wind turbine, diesel generators and pumps are considered as well.

In general the readership of this book includes researchers, students, and engineers who work in the field of renewable energy and specifically in photovoltaic system. Moreover, the book can be used mainly or partially as a textbook for the following courses:

Modeling of photovoltaic systems
Modeling of solar radiation components
Computer application for photovoltaic systems
Photovoltaic theory

The authors of this book believe that this book will helpful for any researcher who is interested in developing Matlab codes for photovoltaic systems, whereas many of the basic parts of system models are provided.

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To my daughter Rayna who will be in a dire need for green energy when she understands the contents of this book and to my wife Aida.

Tamer Khatib

To my daughters Gretchen and Viviane and to my wife Claudia.

Wilfried Elmenreich

CONTENTS

1

MODELING OF THE SOLAR SOURCE

1.1 INTRODUCTION

Solar energy is the portion of the Sun's radiant heat and light, which is available at the Earth's surface for various applications of generating energy, that is, converting the energy form of the Sun into energy for useful applications. This is done, for example, by exciting electrons in a photovoltaic cell, supplying energy to natural processes like photosynthesis, or by heating objects. This energy is free, clean, and abundant in most places throughout the year and is important especially at the time of high fossil fuel costs and degradation of the atmosphere by the use of these fossil fuels. Solar energy is carried on the solar radiation, which consists of two parts: extraterrestrial solar radiation, which is above the atmosphere, and global solar radiation, which is at surface level below the atmosphere. The components of global solar radiation are usually measured by pyranometers, solarimeters, actinography, or pyrheliometers. These measuring devices are usually installed at selected sites in specific regions. Due to high cost of these devices, it is not feasible to install them at many sites. In addition, these measuring devices have notable tolerances and accuracy deficiencies, and consequently wrong/missing records may occur in a measured data set. Thus, there is a need for modeling of the solar source considering solar astronomy and geometry principles. Moreover, the measured solar radiation values can be used for developing solar radiation models that describe the mathematical relations between the solar radiation and the meteorological variables such as ambient temperature,

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humidity, and sunshine ratio. These models can be later be used to predict solar radiation at places where there is no solar energy measuring device installed.

1.2 MODELING OF THE SUN POSITION

As a fact, the Earth rotates around the Sun in an elliptical orbit. Figure 1.1 shows the Earth rotation orbit around the Sun. The length of each rotation the Earth makes around the Sun is about 8766 h, which approximately stands for 365.242 days.

From the figure, it can be seen that there are some unique points at this orbit. The winter solstice occurs on December 21, at which the Earth is about 147 million km away from the Sun. On the other hand, at the summer solstice, which occurs on June 21, the Earth is about 152 million km from the Sun. However, to provide more accurate points, the Earth is closest to the Sun (147 million km) on January 2, and this point is called perihelion. The point where the Earth is furthest from the Sun (152 million km) is called aphelion and occurs on July 3.

For an observer standing at specific point on the Earth, the Sun position can be determined by two main angles, namely, *altitude angle* (α) and *azimuth angle* (θ_S), as seen in Figure 1.2.

From Figure 1.2 the altitude angle is the angular height of the Sun in the sky measured from the horizontal. The altitude angle can be given by

$$\sin\alpha = \sin L \sin\delta + \cos L \cos\delta \cos\omega \tag{1.1}$$

where L is the latitude of the location, δ is the angle of declination, and ω is the hour angle.

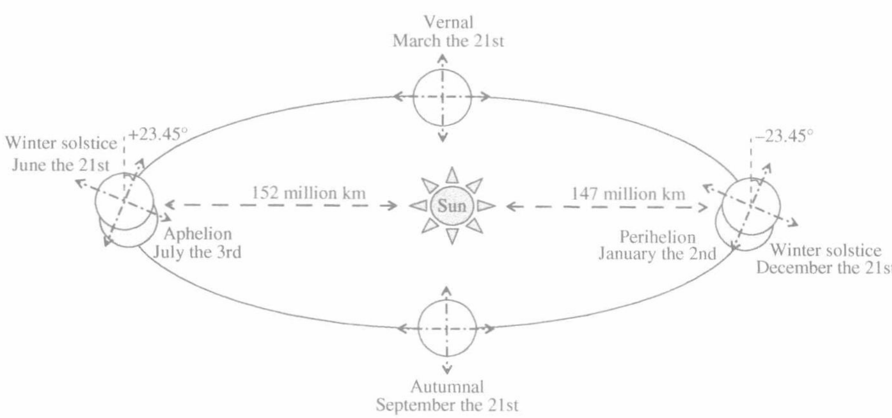

FIGURE 1.1 Earth rotation orbit around the Sun.

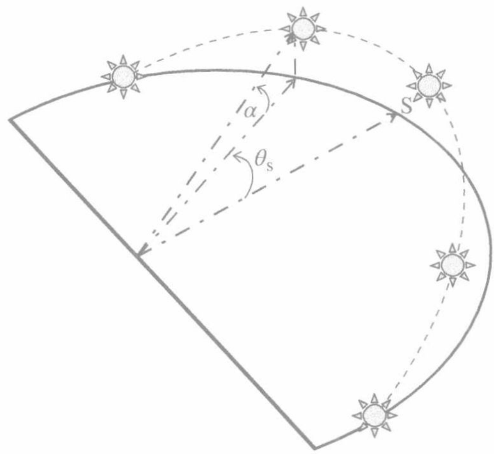

FIGURE 1.2 The Sun's altitude and azimuth angles.

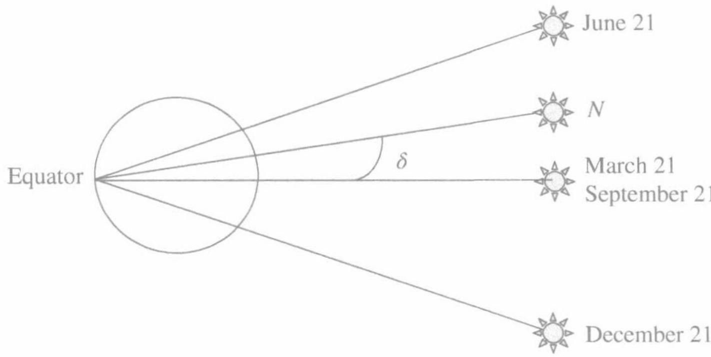

FIGURE 1.3 Solar declination angle.

The angle of declination is the angle between the Earth–Sun vector and the equatorial plane (see Fig. 1.3) and is calculated as follows (results in degree, arguments to trigonomic functions are expected to be in radiant):

$$\delta_S = 23.45°\sin\left[\frac{2\pi(N-81)}{365}\right] \tag{1.2}$$

The hour angle, ω, is the angular displacement of the Sun from the local point, and it is given by

$$\omega = 15°(\mathrm{AST} - 12\ \mathrm{h}) \tag{1.3}$$

where AST is apparent or true solar time and is given by the daily apparent motion of the true or observed Sun. AST is based on the apparent solar day, which is the interval between two successive returns of the Sun to the local meridian. Apparent solar time is given by

$$\mathrm{AST} = \mathrm{LMT} + \mathrm{EoT} \pm 4° / (\mathrm{LSMT} - \mathrm{LOD}) \tag{1.4}$$

where LMT is the local meridian time, LOD is the longitude, LSMT is the local standard meridian time, and EoT is the equation of time.

The LSMT is a reference meridian used for a particular time zone and is similar to the prime meridian, used for Greenwich Mean Time. LSMT is given by

$$\mathrm{LMST} = 15° T_{\mathrm{GMT}} \tag{1.5}$$

The EoT is the difference between apparent and mean solar times, both taken at a given longitude at the same real instant of time. EoT is given by

$$\mathrm{EoT} = 9.87 \sin(2B) - 7.53 \cos B - 1.5 \sin B \tag{1.6}$$

where B can be calculated by

$$B = \frac{2\pi}{365}(N - 81) \tag{1.7}$$

where N is the day number defined as the number of days elapsed in a given year up to a particular date (e.g., the 2nd of February corresponds to 33).

On the other hand, the azimuth angle as can be seen in Figure 1.2 is an angular displacement of the Sun reference line from the source axis. The azimuth angle can be calculated by

$$\sin\theta = \frac{\cos\delta \sin\omega}{\cos\alpha} \tag{1.8}$$

Example 1.1: Develop a program in MATLAB® that calculates the altitude and azimuth angles at 13 : 12 on July 2, for the city of Kuala Lumpur.

Solution

The main parts of the program's structure are described as follows:

- Insert location coordinates (latitude and longitude), day number, and local mean time.
- Calculate angle of declination, equation of time, and LMST.
- Calculate AST and hour angle.
- Calculate altitude angle.
- Calculate azimuth angle.
- Plot results.

```
Modeling of PV systems using MATLAB
%Chapter I
%Example 1.1
%--------------------------------------------------------
%date 2/7/2015 (N=183)
%location Kuala Lumpur, Malaysia, L =(3.12), LOD = (101.7)
L=3.12; %Latitude
LOD=101.7; %longitude
N=183;  %Day Number
T_GMT=8;  %Time difference with reference to GMT
LMT_minutes=792;  %LMT in minutes
Ds=23.45*sin((360*(N-81)/365)*(pi/180));  %  angle  of
  declination
B=(360*(N-81))/364;   %Equation of Time
EoT=(9.87*sin(2*B*pi/180))-  (7.53*cos(B*pi/180))-
  (1.5*sin(B*pi/180)); % Equation of Time
Lzt= 15* T_GMT; %LMST
if LOD>=0
Ts_correction= (-4*(Lzt-LOD))+EoT; %solar time correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %solar time correction
end
Ts= LMT_minutes + Ts_correction; %solar time
Hs=(15 *(Ts - (12*60)))/60; %Hour angle degree
sin_Alpha=(sin(L*pi/180)*sin(Ds*pi/180))+
  (cos(L*pi/180)*cos(Ds*pi/180)* cos(Hs*pi/180)); %altitude
  angle
Alpha=asind(sin_Alpha)   %altitude angle
Sin_Theta= (cos (Ds*pi/180)*sin (Hs*pi/180))./cos(Alpha_i.
  *pi/180); %Azimuth angle
Theta=asind(Sin_Theta) %Azimuth angle
```

ANS: Alpha = 70.04°; theta = −1.13°

Example 1.2: Modify the developed MATLAB code in Example 1.1 to calculate the altitude and azimuth angle profile (every 5 min) for the whole solar day of the 2nd of July for the city of Kuala Lumpur.

Solution

The solar day is defined as the duration from sunrise to sunset. Thus, the altitude and azimuth angles are required to be calculated for each hour from sunrise to sunset. The sunrise and sunset hour angles can be considered equal and calculated as

$$\omega_{ss,sr} = \cos^{-1}\left(-\tan L \tan \delta\right) \tag{1.9}$$