PHOTOVOLTAICS System Design and Practice

HEINRICH HÄBERLIN

WILEY

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SYSTEM DESIGN AND PRACTICE

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To my wife Ruth and my children Andreas and Kathrin, who, while I was writing this book, weren't able to spend as much time with me as they would have liked – and to all those who want to see our society transition to sustainable and responsible electricity generation.

Contents

Foreword

Energy and the concerns it raises for individuals, society at large and the environment, is a more burning issue today than ever before. Evolutions such as climate change, energy security issues, energy market deregulation, energy price fluctuations and the like have made energy the centre of a multi-faceted debate where the need for sustainable energy and improved energy efficiency are taking centre stage as never before. The European Commission's objectives for 2020 in this regard are both courageous and pioneering.

The Stern Report issued by the British government in 2006 noted that global warming and its worldwide economic repercussions constitute the widest-ranging failure of free market mechanisms that the world has ever seen. This report also quantified the economic costs of this evolution. The 'business as usual' attitude that unfortunately still prevails in the business and political communities is going to cost us dearly; and the longer we wait to act, the higher the cost will be. A growing number of politicians, business leaders, and consumers have come to the realization that action must be taken, and that such action will not come cheap.

The timing of this book's publication could not be better. Admittedly photovoltaics is no magic bullet solution for the myriad problems we face but photovoltaics is one of the key technologies that will bring us closest to a sustainable energy supply in the foreseeable and distant future. Many technical and other obstacles remain to be surmounted before photovoltaics can do this, however, the undeniable fact of the matter is that photovoltaics is now the subject of feverish and rapid worldwide development on an industrial scale. The annual growth rates of upwards of 40 percent registered by the photovoltaics industry are all the more remarkable in light of the recent financial crisis, not to mention past economic recessions.

The term photovoltaics is often associated primarily with solar cells and solar modules. As these are the core elements of photovoltaic technology, this mindset makes perfect sense. However, it does not go far enough when it comes to characterizing the energy production of a solar power installation. Only if we regard photovoltaics as an energy system can we begin to make accurate statements concerning its contribution to the energy supply. Moreover, regarding a phenomenon as a system often allows us to connect the dots between theory and practice, paradigm and experience.

As growing numbers of PV installations are put into operation, questions are increasingly being raised concerning their quality and reliability. Only a PV installation that works properly can genuinely contribute to the energy supply. Hence such issues are looming ever larger worldwide. One of the great virtues of the present book is that it places tremendous emphasis on the system related aspects of photovoltaics.

Over the course of his many years of research on the system related aspects of photovoltaics, Prof. Häberlin has accumulated unparalleled experience that is richly detailed in his numerous publications on the subject. He has now made this experience available to a wider public, via this book, which in using its author's experience as a springboard, provides a wealth of insights and highly practical information concerning the design and operation of PV installations. In so doing, this book also addresses an increasingly pressing problem, namely that rapid growth in the photovoltaics industry and other renewable energy sectors will increase the need for qualified individuals in this domain. Thus education and training are a matter of growing importance in this regard.

I would like to on one hand express my gratitude to Prof. Häberlin for having written this book, and on the other congratulate him on his willingness to share his photovoltaics expertise with a wider audience via this book, which I feel will make a significant contribution to the advancement of photovoltaic technology. I am confident that this richly detailed and very complete book will enable numerous photovoltaics engineers, researchers and other professionals to gain greater insight into photovoltaics, and particularly into the practical aspects of this intriguing field.

Stefan Nowak, Ph.D.
Chairman of the International Energy Agency Photovoltaics Power Systems Programme (IEA PVPS)
St. Ursen, Switzerland

Preface

The PV industry has experienced an exponential growth since the appearance of the first edition of this book in German in 2007 and ever-larger PV installations are being realized in an ever-growing number of countries. The tremendous interest shown in the first edition of this book, as well as the extensive positive feedback it elicited, show that photovoltaics, which is discussed comprehensively and in all its complexity in this book, is a topic of tremendous importance nowadays.

Therefore the second edition published also in German in 2010 goes into even greater depth on a number of matters and also explores some aspects of and insights into photovoltaics that were not contained in the first edition. For this second edition, I have extensively revised, updated and expanded the material from the first edition in such a way that, using the information in this book, designers can make very close sizing and yield estimates for PV installations at any site worldwide between 40 °S and 60 °N. In addition to updating my own extremely extensive PV installation monitoring data, I have also included energy yield figures from other countries, thanks to the generosity of the relevant operators who kindly provided data concerning their installations.

Considering the success of the two German books and the expressed interest also from many English speaking PV engineers, it was decided to translate this book into English to make my extended PV experience available also to them. The present book is an exact translation into English of the extended second German edition published in 2010.

Since the finalisation of the German book and the translation, prices for PV modules have considerably dropped further especially in 2011. For large quantities of crystalline modules prices of 1 € per Wp or even somewhat less were offered in autumn 2011, i.e. even less than the lowest values indicated in the book. Therefore the price of PV electricity is now already very close to competiveness with conventional electricity in many countries.

Heinrich Häberlin
Ersigen
October 2011

About the Author

After earning a Masters degree in electrical engineering from ETH Zurich, Heinrich Häberlin became a staff researcher at the ETH Microwave Lab. During this time he developed hardware, software and numerous learning applications for a computerized teaching and learning system that was used at ETH until 1988. He earned a doctorate in 1978, based on the thesis he wrote concerning this system.

From 1979 to 1980, Dr. Häberlin headed a team at the Zellweger Company that worked on the development of hardware and software for microprocessor-based control of a complex short-wave radio system.

In late1980 he was appointed a professor to the engineering school in Burgdorf, Switzerland, where from 1980 to 1988 besides electrical engineering he also taught computer science.

Prof. Häberlin has been actively involved in photovoltaics since 1987. In 1988 he established the Bern University of Applied Sciences Photovoltaics Lab, where he and his staff mainly investigate the behaviour of grid-connected systems. Since 1989 he has also been operating his own PV installation. In 1988 he began testing various PV inverters and in 1990 he initiated a series of lab experiments concerning PV installation lightning protection. Prof. Häberlin's PV Lab has, since 1992, also been continuously monitoring more than 70 PV installations, mainly under the auspices of research projects commissioned by Switzerland's Federal Office for Energy. His lab also carries out specialized measurements of PV installation components for the relevant manufacturers and also works on various EU projects.

Prof. Häberlin has been teaching photovoltaics at Bern University of Applied Sciences since 1989. He is a member of Electrosuisse, ETG, the Swiss TK82 panel of experts on PV installations, and the IEC's International Photovoltaics Standards Committee TC82.

Acknowledgements

I would like to thank all of the private and public sector organizations that kindly provided photos, graphics, data and other documentation for this book. Without these elements, I would not have been able to provide such a detailed and in-depth account of the relevant issues.

I would also like to express my heartfelt gratitude to my past and current assistants, who carried out investigations and analyses in connection with numerous research projects and whose work products I have used in this book. I also owe a debt of gratitude to the following organizations that commissioned and financed the aforementioned research projects: the Swiss Ministry of Energy; the Swiss Ministry of Science and Education; the Bern Canton Office of Water and Energy Resource Management; and various power companies (namely, Localnet, Bernische Kraftwerke, Gesellschaft Mont Soleil, Elektra Baselland and Elektrizitätswerk der Stadt Bern).

My former assistants Christoph Geissbühler, Martin Kämpfer and Urs Zwahlen, and my current assistants Luciano Borgna and Daniel Gfeller, read the manuscript for the first edition of this book in German and pointed out errors and elements that were unclear. My colleagues Dr Urs Brugger and Michael Höckel read certain sections of the first-edition manuscript and provided helpful suggestions.

The manuscript for the second book in German was read by my current assistants Daniel Gfeller, David Joss, Monika Münger and Philipp Schärf, who likewise pointed out errors and elements that were unclear.

I would like to express my gratitude to all of these individuals for their assistance.

Heinrich Häberlin

Ersigen
January 2010

Note on the Examples and Costs

Many of the chapters in this book contain examples whose numbers were in many cases calculated using spreadsheet programs that round off the exact numbers that were originally input. On the other hand, for reasons of space many of the numbers in the tables in Appendix A have been rounded off to two decimal places. Hence, when used for actual calculations, these rounded-off numbers may under certain circumstances differ slightly from the counterpart numbers indicated in the examples.

In several sections of this book, costs of PV modules or PV systems or feed-in tariffs are given in euros. In some cases or examples, especially where the situation in Switzerland is discussed, costs in Swiss francs (SFr) are expressed as their equivalent in euros (€). The exchange rate used in this case was the exchange rate during the finalization of the German book, i.e. 1 Swiss franc is equivalent to about 0.67 euros. Due to the problems on the financial markets, there were extreme variations of this exchange rate in 2010 and 2011 (variation between about 1 SFr $\approx$ 0.67 € and 1 SFr $\approx$ 1 €). For actual values in Swiss francs the actual exchange rate has to be used.

List of Symbols

Symbol	Name	Metric
a	Depreciation rate	%
a_A	Battery depreciation rate	%
a_E	Depreciation rate for electronic installations	%
A_G	Total surface area of a solar generator field (aggregate module surface area)	
a_G	Solar generator depreciation rate	%
A_L	Space required for a ground-based or rooftop solar generator field	m^2
AM	Air mass number	—
a_{MB}	Relative number of shaded modules per string	—
a_{MM}	Relative number of modules per string that exhibit power loss	—
A_Z	Solar cell surface area	m^2
C	Battery capacity	F
C	Capacitance	F
C_E	Solar generator earthing capacitance	F
CF	Capacity factor	—
c_T	Temperature coefficient for a solar generator's MPP output	K^{-1}
di/dt_{max}	Maximum current curve in a lightning leader stroke	kA/μs
d_V	Relative voltage rise at the grid link point	—
e	Electron charge (scope of an electron or proton charge) ($e = 1.602 \cdot 10^{-19}$ A s)	A s
e	Basis for natural logarithms: e = 2.718 281 828	—
E	Energy (in general)	kWh, MJ
e_A	PV installation surface-related grey energy	kWh/m^2 MJ/m^2
E_{AC}	PV installation AC power output	kWh
E_D	Mean daily DC power used by a stand-alone installation	Wh/d
E_{DC}	PV installation DC power output	kWh
$E_{DC\text{-}S}$	Mean DC power output per day and string for a stand-alone installation with MPT	Wh/d
EF	Yield factor = L/ERZ	—
E_G	Band gap energy (usually expressed in eV; 1 eV = $1.602 \cdot 10^{-19}$ J)	eV
E_H	Mean daily energy yield of a hybrid generator	Wh/d
E_L	Total energy produced by a PV installation during its service life	kWh, MJ
e_P	Peak-power-related grey energy in PV installations	kWh/W, MJ/W
ERZ	Energy payback time (time needed to produce grey energy)	a
f	Frequency	Hz
FF	Filling factor for a solar cell, solar module or solar generator	—
FF_i	Idealized filling factor	—

G	Global irradiance (power/surface), usually indicated for the horizontal plane	W/m^2
G_B	Direct beam irradiance, usually indicated for the horizontal plane	W/m^2
G_D	Diffuse irradiance, usually indicated for the horizontal plane	W/m^2
GE	Grey energy	kWh, MJ
G_{ex}	Extraterrestrial irradiance	W/m^2
G_G	Global irradiance on the solar generator plane	W/m^2
G_o, G_{STC}	Irradiance under STC: $G_o = 1$ kW/m^2	W/m^2
H	Total irradiation (energy/area), usually indicated for the horizontal plane	kWh/m^2 (MJ/m^2)
H_B	Total irradiation; direct beam irradiation (usually indicated for the horizontal plane)	kWh/m^2 (MJ/m^2)
H_D	Total irradiation; diffuse irradiation (usually indicated for the horizontal plane)	kWh/m^2 (MJ/m^2)
H_{ex}	Total extraterrestrial irradiation on a plane parallel to the horizontal plane outside of the Earth's atmosphere	kWh/m^2 (MJ/m^2)
H_G	Total irradiation, irradiation on the solar generator plane (energy/area)	kWh/m^2 (MJ/m^2)
I	Electric current (general)	A
i_A	Lightning current in a down-conductor	A
$i_{A\max}$	Peak lightning current in a down-conductor	A
I_{Dceff}	Figure for the DC input current of a stand-alone inverter	A
I_F	Passband current	A
I_L	Charging current	A
$i_{\max}$	Peak lightning current voltage	A
I_{MPP}	MPP current	A
I_{PV}	Solar generator current	A
I_R	Solar module reverse current (= passband current in a solar cell diode)	A
I_S	Saturation current of a diode or solar cell	A
I_{SC}	Short-circuit current of a solar cell, solar module or solar generator	A
$I_{SC\text{-}STC}$	Short-circuit current under STC	A
I_{SN}	Nominal string fuse voltage	A
i_{So}	Short-circuit current induced by lightning current in a conductor loop	A
$i_{So\max}$	Peak induced short-circuit current in a conductor loop	A
i_V	Displacement current induced in a PV installation by a distant lightning strike	A
i_V	Varistor current induced by lightning current	A
$I_{V8/20}$	Requisite nominal varistor current (for an 8/20 μs waveform)	A
$J_{\max}$	Peak current density	A/m^2
J_S	Saturation current density	A/m^2
k	Boltzmann's constant $= 1.38 \cdot 10^{-23}$ J/K	J/K
K_A	Battery costs for stand-alone installations	euros
k_B	Annual operating costs	euros/year
k_B	Shading correction factor (1 for no shading, 0 for full shading)	—
k_C	Proportion of lightning current in a down-conductor	—
K_E	Costs for electronic components such as inverters	euros
k_G	Solar generator correction factor	—
K_G	Costs attributable to a solar generator, site modification, wiring, and so on	euros

k_I	Total harmonic current distortion	—
K_J	Total annual PV installation operating costs	euros/year
k_{MR}	Correction factor for deriving M_{Mi} from M_{MR} for a module frame	—
K_N	Usable battery capacity	Ah
K_S	Cost savings for roof tiles and the like for PV installations that are integrated into buildings	euros
k_T	Temperature correction factor	—
K_x	Battery discharge capacity expressed as x number of hours ($K_x = f(x)$)	Ah
L	Inductance (in general)	H
L	Installation lifetime (in years)	a
L_C	Capture losses	h/d
L_{CM}	Miscellaneous capture losses	h/d
l_{CM}	Standardized miscellaneous non-capture losses: $l_{CM} = y_T - y_A$	—
L_{CT}	Thermal capture losses	h/d
l_{CT}	Standardized thermal capture losses: $l_{CT} = y_R - y_T$	—
L_S	Conductor loop inductance	H
l_S	Standardized system capture losses: $l_S = y_A - y_F$	—
L_S, L_{BOS}	Balance of system losses	h/d
M	Mutual inductance (in general)	H
M_i	Effective mutual inductance, based on total lightning current i	H
M_{Mi}	Effective mutual inductance of a module (based on total lightning current i)	H
M_{MR}	Module frame mutual inductance (based on $i_A = k_C \cdot i$)	H
n_{AP}	Number of parallel-connected batteries	—
n_{AS}	Number of series-connected batteries	—
N_D	Mean annual number of direct lightning strikes	—
N_g	Number of lightning strikes per square kilometre and year	—
n_I	Inverter efficiency (energy efficiency)	—
n_{MP}	Number of parallel-connected modules in a solar generator	—
n_{MS}	Number of series-connected modules in a string	—
n_{MSB}	Number of shaded modules per string	—
n_{MSM}	Number of modules per string that exhibit power loss	—
n_{SP}	Number of parallel-connected strings in a solar generator	—
n_{VZ}	Full-cycle service life of a battery	—
n_Z	Number of series-connected cells	—
n_{ZP}	Number of parallel-connected strings in a solar module	—
P	Effective power	W
p	Interest rate that is to be applied to depreciation	%
P_A	Solar generator DC power output	W
P_{Ao}	Effective (measured) peak solar generator output under STC	W
P_{AC}	AC-side output	W
P_{AC1}	Maximum connectable single-phase nominal inverter output	W
P_{AC3}	Maximum connectable triphase nominal inverter output	W
P_{ACn}	AC-side nominal output of an inverter or a PV installation	W
P_{DC}	DC-side output	W
P_{DCn}	DC-side nominal inverter output	W
PF	Packing factor	—
P_{Go}	Nominal solar generator peak output under STC (aggregate P_{Mo})	W
P_{GoT}	Temperature-corrected nominal solar generator peak output	W
P_{max}	Maximum output (equates to P_{MPP} under STC)	W
P_{Mo}	Nominal module output under STC, according to the vendor's data	W

P_{MPP}	MPP of a solar cell, solar module or solar generator	W
P_{use}	PV installation output power	W
PR	Performance ratio = Y_F/Y_R	—
pr	Instantaneous performance ratio = y_F/y_R	—
PR_a	Annual performance ratio	—
p_{VTZ}	Maximum allowable area-specific solar cell power loss	W/m^2
Q	Watless power (> 0 when inductive)	var
Q_D	Mean daily load consumption for a stand-alone installation	Ah/d
Q_H	Mean daily hybrid solar generator charge for a stand-alone installation	Ah/d
Q_L	Lightning current charge (up to a few hundred milliseconds)	A s
Q_L	Mean daily charge consumption (> Q_D) for a stand-alone installation	Ah/d
Q_{PV}	Mean daily charge provided by a solar generator	Ah/d
Q_S	Lightning current charge (surge current of less than 1 ms duration)	As
Q_S	Mean daily string charge for a stand-alone installation	Ah/d
R	Resistance (in general); real component of a complex impedance $\underline{Z}$	Ω
R_{1L}	Real component of complex single-phase impedance in a conductor between a transformer and grid link point (for inverter connection purposes)	Ω
R_{1N}	Real component of complex single-phase grid impedance (ohmic component)	Ω
R_{1S}	Real component of complex single-phase interconnecting line impedance (with impedance $\underline{Z}_S$) between a grid link point and inverter	Ω
R_{3L}	Real component of complex triphase impedance in a conductor between a transformer and grid link point (for inverter connection purposes)	Ω
R_{3N}	Real component of complex triphase grid impedance (ohmic component)	Ω
R_{3S}	Real component of complex triphase interconnecting line impedance (with impedance $\underline{Z}_S$) between a grid link point and inverter	Ω
$R(\beta,\gamma)$	Global radiation factor = H_G/H	—
$R_a(\beta,\gamma)$	Annual global radiation factor = H_{Ga}/H_a (ratio of annual irradiance figures)	—
R_B	Direct beam radiation factor = H_{GB}/H_B (as in the tables in Section A4)	—
r_B	Lightning sphere radius	m
R_D	Diffuse radiation factor = H_{GD}/H_D	—
R_D	Ground resistance of a grounding installation	Ω
R_i	Inner resistance of a battery or the like	Ω
R_L	Power lead resistance (real component of $\underline{Z}_L$)	Ω
R_M	Shielding resistance; resistance in the cladding of a shielded conductor	Ω
R_N	Inner grid resistance (real component of $\underline{Z}_N$)	Ω
R_P	Parallel resistance	Ω
R_R	Frame reduction factor	—
R_S	Series resistance of a solar cell or conductor loop	Ω
R_T	Medium-voltage transformer resistance (real component of $\underline{Z}_T$)	Ω

R_V	Equivalent (linearized) resistance in a varistor replacement source	Ω
S	Apparent output	VA
S_{1KV}	Single-phase grid short-circuit current at the grid link point	VA
SF	Voltage factor	—
S_{KV}	Triphase grid short-circuit current at the grid link point	VA
$s_{\min}$	Minimum safety gap for hazardous proximities	m
S_{WR}	Apparent triphase output of an inverter	VA
T	Absolute temperature	K
T_C	Cell temperature (variant of T_Z)	°C
T_o, T_{STC}	Reference STC temperature (25 °C)	°C
T_U	Ambient temperature	°C
t_V	AC full-load hours (installation full load P_{ACn})	h
t_{Vb}	AC full-load hours for a PV installation whose power limitation is $P_{AC\text{-}Grenz} < P_{AC\max}$	h
t_{Vm}	AC full load hours for a PV installation based on the installation's peak AC output $P_{AC\max}$ (normally $P_{AC\max}$ differs from P_{ACn})	h
t_{Vo}	PV installation full-load hours, including peak output P_{Go} (under STC)	h
T_Z	Cell temperature	°C
t_Z	Battery depth of discharge	—
T_{ZG}	Irradiance-weighted cell and module temperature	°C
V	Voltage (in general)	V
V_{1N}	Grid phase voltage for a replacement source under open-circuit conditions	V
V_{1V}	Phase voltage at the grid link point	V
V_{1WR}	Phase voltage at the inverter connection point	V
V_{BA}	Bypass diode voltage under avalanche conditions	V
V_G	Battery charge limiting voltage (gassing voltage)	V
V_L	Battery charging voltage; output voltage of an MPT charge controller	V
V_M	Peak voltage induced by lightning current in a module	V
$v_{\max}$	Maximum induced voltage	V
V_{MPP}	MPP voltage	V
$V_{MPPA\text{-}STC}$	PV installation or solar generator MPP voltage under STC	V
V_N	Concatenated grid voltage for a replacement source under open-circuit conditions	V
V_{OC}	Open-circuit voltage of a solar cell, solar module or solar generator	V
$V_{OCA\text{-}STC}$	Open-circuit PV installation voltage under STC	V
V_{Ph}	Theoretical photovoltage $= E_G/e$	V
V_{PV}	Solar generator voltage	V
V_R	Inverse voltage	V
V_{RRM}	Diode inverse voltage	V
V_S	PV installation system voltage	V
V_S	Peak voltage induced by lightning current in a string	V
V_V	Concatenated voltage at the grid link point	V
V_V	Equivalent (linearized) voltage in a varistor replacement source	V
V_V	Peak voltage induced by lightning current in wiring	V
V_{VDC}	Varistor DC operating voltage specified by the vendor	V
V_{WR}	Concatenated voltage at the inverter connection point	V
$V_{\max}$	Peak potential increase relative to remote ground	V

X	Reactance (in general); imaginary component of an impedance $\underline{Z}$	Ω
X_{1L}	Imaginary component of complex single-phase impedance in a conductor between a transformer and grid link point (for inverter connection purposes)	Ω
X_{1N}	Imaginary component of complex single-phase grid impedance (reactance)	Ω
X_{1S}	Imaginary component of complex single-phase interconnecting line impedance (with impedance $\underline{Z}_S$) between a grid link point and inverter	Ω
X_{3L}	Imaginary component of complex triphase impedance in a conductor between a transformer and grid link point (for inverter connection purposes)	Ω
X_{3N}	Imaginary component of complex triphase grid impedance (reactance)	Ω
X_{3S}	Imaginary component of complex triphase interconnecting line impedance (with impedance $\underline{Z}_S$) between a grid link point and inverter	Ω
X_L	Power lead reactance (imaginary component of $\underline{Z}_L$)	Ω
X_N	Grid reactance (imaginary component of $\underline{Z}_N$)	Ω
X_T	Medium-voltage transformer reactance (imaginary component of $\underline{Z}_T$)	Ω
Y_A	Array yield, i.e. full-load P_{Go} hours	h/d
y_A	Standardized solar generator power $= P_A/P_{Go}$	—
Y_F	Final yield, i.e. full-load P_{Go} hours	h/d
y_F	Standardized output power $= P_{use}/P_{Go}$	—
Y_{Fa}	Specific annual energy yield	kWh/kWp and h/a
Y_R	Reference yield, i.e. full-load solar hours	h/d
y_R	Standardized irradiance $= G_G/G_o$	—
Y_T	Temperature-corrected reference yield	h/d
y_T	Temperature-corrected standardized irradiance $= y_R \cdot P_{GoT}/P_{Go}$	—
$\underline{Z}$	Complex impedance $\underline{Z} = R + jX$ (in general)	Ω
Z	Impedance amount (AC resistance)	Ω
$\underline{Z}_{1L}$	Complex single-phase line impedance at the transformer grid link point	Ω
$\underline{Z}_{1N}$	Complex single-phase grid impedance	Ω
$\underline{Z}_{3L}$	Complex triphase line impedance at the transformer grid link point	Ω
$\underline{Z}_{3N}$	Complex triphase grid impedance	Ω
$\underline{Z}_L$	Complex power lead impedance	Ω
$\underline{Z}_N$	Complex grid impedance	Ω
$\underline{Z}_S$	Complex grid impedance in the inverter interconnecting line	Ω
Z_N	Amount of grid impedance	Ω
$\underline{Z}_T$	Complex medium-voltage transformer impedance	Ω
Z_W	DC cable wave impedance	Ω
ΔV_V	Voltage rise at the grid link point	V
ΔV_{WR}	Voltage rise at the inverter connection point	V
α	Lightning protection angle	°
β	Solar generator angle of incidence	°
γ	Solar generator azimuth	°
δ	Solar declination	°
η_{Ah}	Battery ampere-hour efficiency	—
η_E	PV installation energy efficiency	—