A METHOD FOR ESTIMATING

THE LONG-TERM PERFORMANCE OF

DIRECT-COUPLED PHOTOVOLTAIC SYSTEMS

by

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Abstract

This thesis introduces a new method to estimate the long-term performance of direct-coupled and maximum power-tracked photovoltaic (PV) systems without battery storage. A number of models exist for estimating maximum power-tracked system performance, but the maximum power-tracking feature is included here as a benchmark for comparison to direct-coupled system performance, the true object of this research. While the output from either type of PV system is dependent on weather and PV array characteristics, the output from direct-coupled PV systems is dependent on the applied load as well. As a result, estimating the performance of direct-coupled systems is more complex than for maximum power-tracked systems.

The method developed here is computationally simple. A reduced set of hourly weather data is generated from widely available long-term monthly-average global solar and ambient temperature data. Correlations are used to estimate hourly weather variations within a day and daily variations within a month. A small number of "typical day" groups are used to approximate the long-term distribution of daily weather in each month. The "typical days" within each group are assumed to be identical which reduces the number of computations yet, subject to the accuracy of the correlations, retains the accuracy of long-term simulations.

To assess the validity of the new method, a program titled DCPVSIMP (for Direct-Coupled PV model, simplified version) was written. Five potential I-V curve sub-

models for this program were evaluated; the one which was selected corresponded well with a large sampling of experimental I-V curve data from outside sources, and the information required to use it is commonly available from PV manufacturers. A detailed version of this program, identical in all respects except that it uses hourly TMY data, titled DCPVDET, was also written to provide a basis for evaluating the weather generation component.

Both the DCPVSIMP and DCPVDET versions were compared to two established models for maximum power-tracking systems, PVFORM and PV f-Chart. Monthly and annual estimates were within :t 1 % relative to PVFORM and + 5 to 6% relative to PV f-Chart. PV f-Chart includes a variable correction factor which decreases estimates of the absorbed radiation at off-normal incidence angles. For performance estimates at moderate northern latitudes the overall effect of this term is about a 5% decrease in annual output The difference between the DCPVDET model and a "5 typical day" version of the DCPVSIMP model was found to be less than 1 % for maximum power-tracking systems.

Monthly and annual performance for over 800 cases using the DCPVDET model, based on three locations and a large variety of direct-coupled resistive, fixed voltage, and DC motor loads, was compared to 3, 5, 10, and 20 "typical day" versions of the DCPVSIMP model. The overall annual % root mean square (RMS) difference between the two models ranged from 3.8% for the "3 typical day" version to 3.2% for the "20 typical day" version, with most of the reduction in the % RMS difference occurring between the 3 and 5 "typical day" versions (3.4% RMS for the 5 day version). For all versions the % mean bias difference (MBD) was less than 1%. The worst monthly results ranged between 5 to 6% RMS among the four versions tested, with a % MBD of less than 1 %.

The body of the report includes a derivation of the new direct-coupled performance estimating method and a description of the DCPVSIMP and DCPVDET models, statistical evaluations of the models and their components, and a set of graphs illustrating typical applications of the DCPVSIMP model for direct-coupled system design.

Acknowledgments

4:30 AM in the Solar Lab, *naturally*. But it feels great; after 16 months of stumbling around deep in research hell' and 3 1/2 more spent noodling with an endless stream of plots, equations, and dangling modifiers, if Mr. Goodprinter cooperates, I can download this baby onto an unsuspecting planet by daybreak. Despite the all-nighters, the steady diet of cardboard pizza, battling the equipment, and risking it all in a building with a Swiss cheese roof and a hurricane ventilator that swirls gases of unexplained origin ("it smerrs bad, but it woorn't hoolt you"), it doesn't seem so bad now. Hey, where do you sign up for the Ph.D?

It's going to be hard to leave the Solar Lab team. I'm thankful to *Dr* Johnny.Reindl for the time and effort you've spent helping me with research ideas, sharing your computer wizardry, listening to the long version of everything, and for a lot of laffs. Also, to *Dr* Johnny2.Cummings, for his careful critiques and tenacious pursuit of anything correct. Or something like that. The friendship of these two and of the rest of this gang (Fig. A, Blake, Manni, Harald, Diane, and Frank) has made the time here fun and worthwhile.

I am especially grateful to Dr Jack Duffie and to my advisors, Dr Sandy Klein and Dr Bill Beckman, for their friendship and for giving me the opportunity to study here and for coming up with the idea for this project and for having the confidence to let me veer off course with it, too.

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* from Minnerly, B.V., UW-Madison Solar Energy Laboratory, 1988I

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Nomenclature

A	Completion factor
a,b	Constants in Liu and Jordan correlation
AC	Alternating Current
Cl,C2	Constants in MIT model
C_{STAT}	Static torque loss constant, N-m
C_{VISC}	Viscous torque loss constant, N-m-s
D	Diode diffusion factor
DC	Direct Current
EMF	Electromotive Force, Volts
F	Cumulative fraction of days per month
F	Objective function
F.F.	Fill Factor, dimensionless
G_{SC}	Solar constant, 1353 W/m2
H	Total Dynamic Pressure Head, meters
H	Total horizontal radiation, KJ/m2-day
H_D	Daily diffuse radiation, KJ/m2-day
H_O	Daily extraterrestrial horiz. radiation, KJ/m2-day fIR Hour
HRX	Dimensionless hour I Current, Amps
I_D	Diode current, Amps
I_L	Light-generated current, Amps
I_O	Reverse saturation current, Amps
k	Boltzmann constant, 1.381E-23 loules/Kelvin

k	Motor dimensionless flux coefficient
K_{MAX}	Maximum clearness index
K_{MIN}	Minimum clearness index
K_T	Clearness index
K_T	Monthly-average clearness index
kWh	Kilowatt-hour
L3P	Lumped, 3 Parameter I-V Model
L4P	Lumped, 4 Parameter I-V Model
2M5P	Lumped 2 Mechanism, 5 Parameter I-V Model
2M6P	Lumped 2 Mechanism, 6 Parameter I-V Model
L_A	Armature Inductance, Henrys
L_F	Field Inductance, Henrys
LINEAR	Simple linear maximum power only model
M_{AF}	Mutual Armature-Field Inductance, Henrys
MBD	Mean Bias Difference
MIT	Mass. Inst. of Tech. I-V Model
MPT	Maximum Power Tracker
n	number of mechanisms
N	Day of year
n,p	negative, positive charges
NCS	Number of cells in series
NMSEI	New Mexico Solar Energy Institute

NP	Number in Parallel
NS	Number in Series
P	Power, Watts
PCU	Power Conditioning Unit
PV	Photovoltaic
Q	Volumetric flowrate, m3/sec.
q	Electron Charge constant, 1.602E-19 Coulombs
R_A	Armature Resistance, Ohms
R_B	Ratio of tilt/horiz. beam radiation
r_D	Hourly fraction of daily diffuse radiation
R_F	Field Resistance, Ohms
R_L	Load Impedance or Resistance, Ohms
RMS	Root mean square
R_S	Apparent series resistance, Ohms
R_{SH}	Apparent shunt resistance, Ohms
r_T	Hourly fraction of total daily radiation
SW	Specific weight of water, 9807 N/m3
T	Temperature
T_C	Cell Temperature
T_{LOAD}	Load torque, N.m
T_{LOSS}	Loss torque, N.m
TMY	Typical Meteorological Year
U_L	Overall loss coefficient, W/m2.K

V	Voltage, Volts
Z	Consolidating teml for algebraic simplification

Greek Symbols

β	Temperature coefficient of maximum power, l/°C
δ	Declination, degrees
ε_{A}.	Armature EMF, Volts
ε_{G}	Bandgap energy, Volts
η	electric conversion efficiency
γ	Dimensionless curve fit factor
λ	Bendt correlation variable
Λ	Consolidating term for algebraic simplification
μ_{ISC}	Temperature coefficient of short circuit current, Amps
μ_{VOC}	Temperature coefficient of open circuit voltage, Volts
ω	Hour angle, degrees
ω	speed, radians/sec.
ω_{S}	Sunset angle, degrees
φ	Permanent magnet flux, Webers
φ	Latitude, degrees
Φ	Irradiance, W/m^2
$(\overline{\tau\alpha})$	Transmittance-Absorptance product
ζ	Bendt correlation variable

Subscripts

A, AMB	ambient

DET	detailed
KNOWN	given condition
MP	maximum power
NEW	new condition
NOCT	Nominal Operating Cell Temperature
OC	open circuit
OPT	optimum
P	pump
REF	reference condition
SC	short circuit
SIMP	simplified