

**TIME SERIES MODELING
OF
HYBRID WIND PHOTOVOLTAIC
DIESEL POWER SYSTEMS**

by
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A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
(Mechanical Engineering)

at the
UNIVERSITY OF WISCONSIN - MADISON
1996

ABSTRACT

Renewable energy systems, especially wind turbines, are often proposed as additions to diesel power systems. The intended role of renewable components in such systems is to reduce fuel requirements and overall costs. In many parts of the world, the expense and logistic effort required for diesel fuel deliveries can be very high. In most cases, wind turbines and/or photovoltaic modules are employed, often as retrofits to diesels already in operation.

The potential economic benefit of hybrid power systems is offset, to some extent, by associated increases in capital cost and complexity. Technical challenges include power management strategies and maximizing the benefits attributed to the renewable energy components. An effective approach to understanding hybrid power systems is to simulate their operation using time-series weather and loads data from a specific location. A modular approach to simulation allows for comparative analyses of various system configurations.

This thesis describes the creation and application of a modular simulation of hybrid power systems. The application has been created using TRNSYS, a transient system simulation environment developed and maintained at the Solar Energy Laboratory (SEL) at the University of Wisconsin-Madison. In order to build the system simulator, several component models were newly created, and several existing component models were modified. New wind turbine, wind cluster, power converter, diesel engine and diesel engine controller components were created for the hybrid simulator. Existing storage battery and data-reading software was modified for use in the application.

A major portion of this work was devoted to the development of the wind turbine and wind cluster models, including their computer codes. The wind turbine component and wind cluster components described in this thesis are the first detailed wind energy components developed for TRNSYS. The wind cluster component is the first time-series implementation of a wind turbine \array" model. Hybrid systems are an excellent application for the exercise of these component simulations.

Simulations of a hypothetical hybrid application in Wisconsin are presented. The results demonstrate the value of a modular design approach for optimizing system design. In addition, it is shown that the combination of wind and PV in a hybrid power system increases the load matching of the renewable component of such systems in Wisconsin.

ACKNOWLEDGMENTS

The past eighteen months have been an incredible experience for me. I don't know if I am the oldest person, at 41, to complete a Master's degree at the Solar Energy Laboratory, but by the way I feel at this point, *I must be!* I could not have pulled this off without the well-timed support of my Mom, my sister Jane, my brother Dennis, and especially my Dad. I want to thank uncle Bob and aunt Andree for supporting the idea in the first place, and to my step-mom Christina and my sisters Kate and Eileen for telling me they love me. I've missed John Zinner and John Scheider, who've been great friends all along.

My research was co-sponsored by the Wisconsin Energy Bureau, and by the University of Wisconsin-Madison. I would like to thank both Don Wichart and Dan Moran of the Energy Bureau for being supportive of my work, and for being good friends to me over the course of the project.

This project would not have come to fruition if not for the timely efforts of Sandy Klein and Bill Beckman to propose for the Energy Bureau grant for this work and ask me to participate. I am deeply grateful to Bill, Sandy and John Mitchell for their guidance and support. Bill is a great manager and motivator; he even made me think all this was easy! Sandy's brilliance has inspired awe; he has the quickest mind and e-mail response time of anyone I've ever known. John has incredible insight into solving tough problems; he was there to help me in the exact way I needed help at the time I needed it the most. Thank you also, Professor Don Ermer, for introducing me to W.E. Deming: "Survival is not mandatory."

Professionally, I want to especially recognize Bill Heronemus for the primary inspiration for this amazing career in renewables, and Bill Beckman for reinforcing it. Thanks go to Peter Lissaman for showing me how to make money at it! As Albert Einstein once said, "I stand on the shoulders of giants."

My time here at the Solar Lab would not have been so productive, if not for the help and great companionship of Nate Blair. He is the only person I know who can be interrupted in the middle of an interruption, up to five, six, seven or more levels, and still be enjoyable to be around. I will always remember fondly my friends: "Al" Al-Ibrahim, Matt Bauer, Stefan Behschnitt, John Bell, Olaf Eckardt, Peter Gallo, Annette Gerth, Marion Hiller, Jim Kelsey, Jeorg Kirchoff, Quing Kou. Ian McIntosh, Roger Rabehl, Steve Rottmayer, Dave Summers, Jay Trzesniewski, Paul Williams, and Steve Zehr. Who would believe I went to grad school with a Major Flake and Doctor Jekel, otherwise known as Barrett and Todd! Special thanks go to Shirley Quamme, for being so nice to me --and keeping my precious coffeepot going!

I dedicate this thesis, this work, to my father, Daniel Joseph Quinlan. I will never forget him. And to uncle Roger Peterson, who demonstrated for me that if you have a powerful passion for something, something truly good, the world will clear a path for you.

How often, over the course of completing this work, have I thought of Adriane and Alex. It is so important for them to have a world that will sustain them: to show that there is a way. I will always be in their debt for suffering my long absences over the last eighteen months. Type 85 and 88 are titled in honor of the years they were born. I missed them so much, too.

Finally, I truly owe the greatest debt of all to the woman of my life, Aletta Schaap. In my absence, she managed to finish earthquake repairs, move, do a great job with Alex and Adriane, even deal with me! I love her so much.

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NOMENCLATURE

Variables

A	=	area of PV array (m ²)
A_r	=	rotor area (m ²)
B	=	number of blades
B_p	=	barometric pressure (mm Hg)
c	=	the transverse crosswind axis in the d, c coordinate system (m)
C_d	=	coefficient of drag (dimensionless)
CP	=	number of cells in parallel
C_p	=	coefficient of performance (dimensionless)
CS	=	number of cells in series
C_T	=	rotor thrust coefficient (dimensionless)
D	=	drag force (N)
d	=	the longitudinal downwind axis in the d, c coordinate system (m)
Dia	=	rotor diameter (m)
DOD	=	battery depth of discharge (fraction)
E	=	energy (Joules, kWh)
E_{sc}	=	open circuit voltage, charge (V)

E_{sd}	=	open circuit voltage, discharge (V)
g	=	gravitational constant (m/s^2)
G_c	=	small valued coefficient of battery SOC
G_d	=	small valued coefficient of battery SOC
η	=	charging efficiency
I	=	current (Amperes)
$I_{c,tol}$	=	battery iterative parameter
I_{di}	=	battery curve fitting parameter
K_{di}	=	battery curve fitting parameter
M_c	=	battery I-V cell type parameter
M_d	=	battery I-V cell type parameter
N	=	total number of turbines
n	=	turbine n, also the North axis in the E/N coordinate system
NP	=	number of modules in parallel
NS	=	number of modules in series
P	=	power extracted (W)
p	=	air pressure (N)
P_{loss}	=	battery power losses
P_R	=	wind turbine rated power output (kW)
P_R^+	=	pressure upwind of wind turbine rotor
P_R^-	=	pressure downwind of wind turbine rotor
Q	=	torque (N-m)
Q_c	=	battery capacity parameter on charge
Q_d	=	battery capacity parameter on discharge
Q_M	=	battery rated capacity
R	=	ideal gas constant ($287m^2/s^2K$), also rotor radius (m)
R_c	=	battery internal resistance on charge
R_d	=	battery internal resistance on discharge
r	=	radial distance from rotor or rotor wake centerline (rotor radii)
sfc	=	specific fuel consumption (g/kWh)
SOC	=	battery state of charge (fraction)
T	=	temperature ($^{\circ}C$)
t	=	time (sec, hour, year)

U	=	free-stream wind velocity in the principal direction (m/s)
U_{ci}	=	wind turbine cut-in wind speed (m/s)
U_{co}	=	wind turbine cut-out wind speed (m/s)
U_D	=	normalized wind speed deficit in a turbine wake (fraction)
U_d	=	downwind wind speed (m/s)
U_r	=	wind speed at the local rotor location (m/s)
U_{ra}	=	wind turbine rated wind speed (m/s)
\bar{U}	=	average free-stream wind velocity in the U direction (m/s)
U'	=	turbulence intensity in the U direction
\bar{V}	=	average free-stream wind velocity in the V direction (m/s)
V	=	free-stream wind velocity in the lateral direction (m/s)
V_c	=	battery cutoff voltage on charge
V_{bat}	=	battery voltage
V_{contr}	=	discharge cutoff voltage
V_d	=	battery cutoff voltage on discharge
V_o	=	voltage (Volts)
V'	=	turbulence intensity in the V direction
W	=	free-stream wind velocity in the vertical direction (m/s)
\bar{W}	=	average free-stream wind velocity in the W direction (m/s)
W'	=	turbulence intensity in the W direction
X	=	downwind distance from upwind rotor (upwind rotor radii)
x	=	longitudinal downwind distance measured in rotor (upwind) radii
Z	=	ground elevation above sea-level (m)
z	=	height above ground (m)
α	=	exponent of the wind shear power equation (dimensionless)
η	=	efficiency of wind turbine, cluster or diesel engine (fraction)
ρ	=	air density (kg/m ³)
λ	=	tip-speed ratio (dimensionless)
σ	=	transverse (crosswind) turbulence intensity
θ	=	wind direction (degrees from North)

Variable Descriptors

<i>amb</i>	- ambient
<i>avg</i>	- average
<i>batt</i>	- battery
<i>C</i>	- charge
<i>c.v.</i>	- control volume
<i>ci</i>	- cut-in
<i>cluster</i>	- cluster
<i>co</i>	- cut-out
<i>D</i>	- discharge
<i>dem</i>	- demand
<i>diesel</i>	- diesel
<i>elec</i>	- electrical
<i>elev</i>	- elevation
<i>high</i>	- high condition
<i>hub</i>	- hub, rotor centerline
I_{bat}	- battery current
<i>IC</i>	- internal combustion
<i>load</i>	- load
<i>loss</i>	- loss
<i>low</i>	- low condition
<i>max</i>	- maximum
<i>mech</i>	- mechanical
<i>min</i>	- minimum
<i>nom</i>	- nominal
<i>oc</i>	- open circuit
<i>off</i>	- off condition
<i>on</i>	- on condition

<i>PV</i>	- photovoltaic
<i>rated</i>	- rated
<i>ref</i>	- reference
<i>sc</i>	- short circuit
<i>sfc</i>	- specific fuel consumption
<i>sys</i>	- system
<i>tot</i>	- total
<i>WT</i>	- wind turbine

Acronyms

AWEA	American Wind energy Association
CanWEA	Canadian Wind Energy Association
DNR	Wisconsin Department of Natural Resources
IC	Internal Combustion
IEA	International Energy Association
MG&E	Madison Gas & Electric Co.
NREL	National Renewable Energy Laboratory
PV	Photovoltaic
REAP	Renewable Energy Assistance Program
SEL	Solar Energy Laboratory
TRNSED	TRNSYS Editor
TRNSHELL	TRNSYS Shell
TRNSYS	Transient Systems Simulator

UCS	Union of Concerned Scientists
UMass	University of Massachusetts
UW	University of Wisconsin
WEPCO	Wisconsin Electric Power Co.
WP&L	Wisconsin Power & Light Co.
WPS	Wisconsin Public Service Corporation