TIME SERIES MODELING
OF
HYBRID WIND PHOTOVOLTAIC
DIESEL POWER SYSTEMS

by
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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.

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NOMENCLATURE

Variables

A	=	area of PV array (m2)
Ar	=	rotor area (m2)
B	=	number of blades
Bp	=	barometric pressure (mm Hg)
c	=	the transverse crosswind axis in the *d, c* coordinate system (m)
Cd	=	coefficient of drag (dimensionless)
CP	=	number of cells in parallel
Cp	=	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)
Esc	=	open circuit voltage, charge (V)

Esd	=	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 $\left(287 m^2/s^2 K\right)$, 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 (°C)
t	=	time (sec, hour, year)

U	=	free-stream wind velocity in the principal direction (m/s)
Uci	=	wind turbine cut-in wind speed (m/s)
Uco	=	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)
Ura	=	wind turbine rated wind speed (m/s)
$\overline{U}$	=	average free-stream wind velocity in the U direction (m/s)
U'	=	turbulence intensity in the U direction
$\overline{V}$	=	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
Vo	=	voltage (Volts)
V'	=	turbulence intensity in the V direction
W	=	free-stream wind velocity in the vertical direction (m/s)
$\overline{\mathrm{W}}$	=	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/m3)
λ	=	tip-speed ratio (dimensionless)
σ	=	transverse (crosswind) turbulence intensity
θ	=	wind direction (degrees from North)

Variable Descriptors

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

PV	- photovoltaic
rated	- rated
ref	- reference
sc	- short circuit
sfc	- specific fuel consumption
sys	- system
tot	- total
WT	- 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