TIME SERIES MODELING
OF
WIND POWER SYSTEMS

Prepared by:
P.J.A. Quinlan
W. A Beckman
S.L. Klein
J.W. Mitchell
SOLAR ENERGY LABORATORY
UNIVERSITY OF WISCONSIN
Madison, WI 53706

Prepared for:
DEPARTMENT OF ADMINISTRATION
WISCONSIN ENERGY BUREAU
P.O. Box 7868
Madison, WI 53707-7868

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ABSTRACT

This report describes the creation and use of time-series simulations of wind power systems 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 simulate both single turbines and clusters of wind turbines, several component models in TRNSYS were created, and several existing component models were modified. ARCView Geographical Information Systems (GIS) output data for a prospective site in DePere, Wisconsin provided input turbine array data for the simulation. Coupling of GIS spatial information with TRNSYS temporal analysis provided powerful analytic and optimization capabilities not otherwise available in either environment. The wind turbine component and wind cluster components described in this report 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. This is also the first-known use of coupled GIS and time-series tools. The DePere, Wisconsin site was shown to be attractive location for a wind energy project composed of wind turbines.

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TABLE OF CONTENTS

LIST OF FIGURES

Chapter 3

Chapter 4

Chapter 7

LIST OF TABLES

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	=	coefficient of performance (dimensionless)
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)
g	=	gravitational constant (m/s^2)
N	=	total number of turbines
n	=	turbine n, also the North axis in the E/N coordinate system
P	=	power extracted (W)
p	=	air pressure (N)

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)
R	=	ideal gas constant $\left(287 m^2/s^2 K\right)$, also rotor radius (m)
r	=	radial distance from rotor or rotor wake centerline (rotor radii)
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'	=	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
c.v. - control volume
ci - cut-in
cluster - cluster
co - cut-out
elec - electrical
elev - elevation
hub - hub, rotor centerline
max - maximum
mech - mechanical
min - minimum
nom - nominal
off - off condition
on - on condition
rated - rated
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
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