November 2001 • NREL/CP-500-30563

Conference Paper

RPM-SIM–Based Analysis of Power Converter Applications in Renewable Energy Systems

Preprint

Jan T. Bialasiewicz
Department of Electrical Engineering
University of Colorado at Denver

Eduard Muljadi and R. Gerald Nix
National Renewable Energy Laboratory

To be presented at the IEEE–IECON 2001 Conference
Denver, Colorado
November 29–December 2, 2001

wable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

NOTICE

The submitted manuscript has been offered by an employee of the Midwest Research Institute (MRI), a contractor of the US Government under Contract No. DE-AC36-99GO10337. Accordingly, the US Government and MRI retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

♻ Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

RPM-SIM–Based Analysis of Power Converter Applications in Renewable Energy Systems

Jan T. Bialasiewicz
Department of Electrical Engineering
University of Colorado at Denver
Denver, Colorado
jtbialas@carbon.cudenver.edu

Eduard Muljadi and R.Gerald Nix
National Wind Technology Center
National Renewable Energy Laboratory (NREL)
Golden, Colorado
eduard_muljadi@nrel.gov

Abstract — **This paper describes the inclusion of a power converter in the simulation of power systems that use renewable energy sources. This paper will present two major roles of the power converter. In an interconnected grid, a power converter can be utilized as a reactive power compensator or an active filter. With a battery on the DC bus, the power converter can function as an energy buffer that stores energy during peak power production and restores energy during low power production. In an isolated operation, the power converter dictates the frequency and regulates the output voltage of the system. In addition, it balances the power in the systems.**

I. INTRODUCTION

With the recent energy crisis in California, the use of renewable energy is receiving increased attention. In renewable energy systems, several energy sources can be combined to supply the main load, which helps to save fuel and reduce pollution.

Using a power converter to control an electric machine began in motoring applications. Later on, power converters came into use in generating operations. In any new generating equipment, it is likely that power electronics components are used in different parts of the equipment.

Several renewable sources can be combined to supply a group of loads (such as village load), an application that has proved successful. In a system on an interconnected grid, the system's frequency is dictated by the grid's frequency. The synchronous generator or other reactive power supports in the power system, or both, regulate the voltage. Renewable energy sources are often used in remote areas where an interconnected grid is not available. In such cases, a diesel generator or a power converter that stores energy can be used to regulate the frequency and the voltage. For example, combinations of pollution-free wind turbines and photovoltaic (PV) panels with diesel generators are used in isolated places where the transport of fuel oil to the site is expensive, where the production of energy is limited by weather conditions, or where pollution levels are regulated. These systems can significantly reduce annual diesel fuel consumption, which minimizes fuel costs and pollution levels. In other applications, a power converter with energy storage (i.e., a battery system) is included in the system with or without diesel generator.

Without an existing interconnected grid or a diesel generator on the system, the power converter must regulate the system's frequency and voltage. However, to take full advantage of the wind or the solar energy resource during periods of maximum availability, a proper control system must be designed for that particular application. The system must maintain power quality, as measured by electrical performance. To ensure stability, power quality, and reliability, each new system should be simulated before it is implemented in the field. The simulation is intended to confirm that a particular control strategy results in the desired system performance or to reveal necessary design modifications, or both.

Using the VisSim™[1] visual environment, we developed a modular simulation system called RPM-SIM [1-3] to facilitate a low-cost application-specific study of the system dynamics of wind–solar–diesel hybrid power systems. With a library of the power system and renewable energy source modules available, it is easy to set up a particular system configuration. Although some simulation studies require that the existing modules be modified or that specialized modules be included, or both [4], such modifications can be done rather quickly. In this paper, we emphasize the tools that RPM-SIM offers for analyzing the performance of autonomous renewable energy systems that include power converters. These applications may involve only the inverter used to connect the battery bank or a PV array, or both. They can also comprise a more complex power converter that consists of a rectifier, a DC bus, a DC/DC converter, and an inverter. Such a power converter may be used to connect a small wind turbine to the system. In some applications, the master function of frequency and voltage control can be interchanged between the diesel generator and the inverter. Our simulation tool enables the programming of the required switching sequence.

Many researchers have recognized the need for a tool that would facilitate the analysis and design of hybrid power systems. Jeffries performed an interesting study of

---

[1] VisSim is the trademark of Visual Solutions.

modeling efforts of wind/diesel systems [5]. Among those who have developed dynamic models of wind/diesel systems (in chronological order) are Tsitsovits and Freris [6], Pierik and De Bonte [7], Papadopulos et al. [8], Uhlen and Skarstain [9], Manwell et al. [10], Papadopulos et al. [11], Lundsager et al. [12], Binder [13], Jeffries et al. [14], and Ladakakos et al. [15]. Of the various simulation tools, we believe that our simulator has the largest selection of modules and control strategies. The RPM-SIM is the first dynamic hybrid system simulator with a symbolic graphical user interface. Figure 1 is a single-line diagram of a generic renewable energy system. The figure shows the principal modules of RPM-SIM. All elements of the simulated system are connected to one module, called the point of common coupling (PCC). The other principal modules are the diesel generator (DG); the alternating current (AC) wind turbine generator (WTG) with the induction generator and the wind speed time series as the input; the rotary converter (RC) with the battery bank (BB); the inverter with the PV array (which may be replaced by the battery bank or a small wind turbine); the village load (VL), and the dump load (DL). R+jX represents the transmission-line impedance and PFC represents the power- factor-correcting capacitors.

In all electrical simulations, we use the d-q axis convention and synchronous reference frame. In electric machine and power system analysis, it is common to use the transformation from three phase quantities—a, b, and c—into the d-q axis. Known as Park's transformation, this technique was pioneered by Park [16] and Stanley [17]. In 1965, Krause and Thomas [18] generalized the d-q transformation for an arbitrary reference frame. Park's transformation has the unique property of eliminating all time-varying inductances from the voltage equations. Ong [19] also uses this transformation for dynamic simulation of electric machinery.

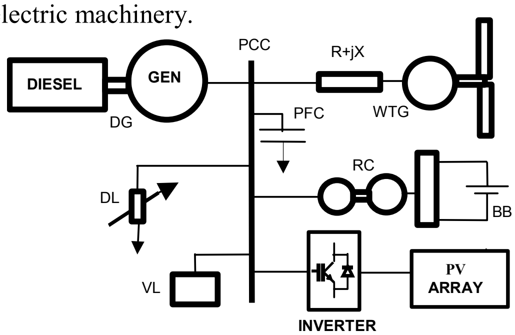

Figure 1. Principal modules of the RPM-SIM included in a single-line diagram of a generic renewable energy system

For all modules included in the simulator, we assumed (for both real and reactive power) a general power sign convention—the power *absorbed* is displayed as negative and the power *generated* is displayed as positive. This power convention simplifies the interpretation of the simulation results. In particular, it facilitates interpreting the instantaneous power balance.

In the sections that follow, we first describe the modules of the simulator. Next, we concentrate on the mechanism that serves to switch the master function between the diesel generator and the inverter. To illustrate the simulator's performance and usefulness, we present a case study of a system that includes a wind turbine with furling control connected to the system through a power converter. Finally, we discuss the potential applications of the simulator and the work planned to expand its modeling capabilities.

II. SIMULATOR MODULES

The *diesel generator module* includes models of the diesel engine and the synchronous generator, the engine speed control block, and the voltage regulator. The engine speed control block generates the fuel/air ratio to keep the frequency constant. The voltage regulator determines the field current of the synchronous generator necessary to keep the voltage constant under varying load conditions. In addition, the user can set the minimum diesel power as a required percentage of the rated value.

*The AC wind turbine module s*imulates two-step conversion of wind power to electrical power. In the first step, wind power is converted to mechanical power. In the second step, electrical power is obtained from the induction generator connected to the line. The wind speed, which constitutes the input signal to the alternating current wind turbine (ACWT) module, is represented in time series. For a small wind turbine, a permanent magnet generator is used. A furling mechanism can be added to control the wind turbine in regions with high wind speeds.

The *dump load module* is composed of parallel resistive loads. The principal purpose of the dump load is to keep the diesel-generated power above a user-prescribed fraction of its rated power. Under special circumstances, it can also be used to control the frequency. Either control strategy dynamically determines the number of the dump load elements to be connected in parallel.

The *village load module g*enerates the q- and d-components of the utility load current. The user declares the rated real power consumption and the power factor and can choose between fixed load and the load profile. The load information is placed in a data file.

The *rotary converter/battery bank assembly* consists of a battery bank and two machines: (1) a DC machine and (2) a synchronous machine. The rotary converter/battery bank assembly can be set up to operate in the synchronous condenser mode. In this mode, the assembly can provide or absorb reactive power, which is accomplished by setting the battery reference power to zero, i.e., maintaining zero shaft torque and zero real power output. The functionality of the rotary converter is similar to the inverter (which is explained below) except that the rotary converter's response is much slower than that of an inverter.

The *inverter* can work in either master mode or slave mode. In the master mode, the inverter controls the system's frequency and voltage when the diesel is disconnected. The power exchange is determined by the system's power balance. In the slave mode, the user specifies the real and reactive power required to be generated or absorbed. The diesel generator or the grid handles the voltage and the frequency control. The transfer from slave mode to master mode is determined based on the control strategy designed by the power plant designer or operator.

PV arrays are commercially available in modules. The PV modules are used to build an array and their I-V characteristics are considered as I-V characteristics of the elementary PV array unit. In our model, we introduced a single solar cell as this elementary unit. Consequently, when setting up the simulation with commercial PV arrays, the user must declare a number of modules in one row or connected in series, as well as a number of module rows connected.

III. INTERACTION OF THE POWER CONVERTER WITH POWER SYSTEMS

The inverter simulated is a voltage source inverter capable of generating constant frequency and constant voltage on the grid side. In the simulation, we assumed that only the fundamental components of the voltage and current exist.

Figure 2 shows a hybrid power system with one wind turbine, one power converter, one diesel generator, and a village load. The stored energy is used to balance the power in the systems. Two types of operations are considered. In the first, the power converter acts as a master control. In this operation, the switch SW is in position A, the power converter acts as a master, and the power converter output controls frequency and voltage. The diesel generator is disconnected from the grid. The energy storage will take the balance of the power consumed and the power generated by the wind turbine. In the second type of operation, the switch SW is in position B and the power converter acts as a slave. In this operation, the diesel generator is connected to the grid and regulates the frequency and the voltage. The power converter can be programmed to store a given amount of energy or to produce a certain amount of energy to or from the battery storage.

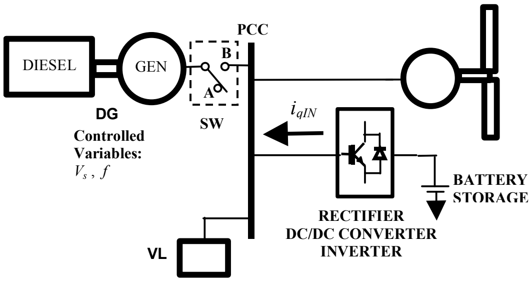

Figure 2. Wind turbine generator connected to the grid

The switching between the master and slave operation takes place in a system with a diesel generator and another energy source connected to the system through the inverter. The following states describe the instantaneous system operation:

STATE 1: Inverter as a master (controls voltage and frequency; the DG is disconnected)

STATE 2: System started with the DG as the master (the inverter operates as a slave)

STATE 3: The DG synchronization starts and is followed by switching the master function to the DG.

In particular, if we have only the inverter on the system, the system is in STATE 1 all the time. If we start with the DG and turn it off and on, we have the following sequence of states:

STATE 2, STATE 1, STATE 3, STATE 1, STATE 3, STATE 1, STATE 3, . . .

When we start with the inverter as a master (DG off), then turn the DG on and off, we have the following sequence of states:

STATE 1, STATE 3, STATE 1, STATE 3, STATE 1, STATE 3, . . .

The user must program the required sequence of state switching using the programming/monitoring guide that comes with the simulation package. In both STATE 2 and STATE 3 (and when the DG is contolling voltage and frequency), the user can additionally program the commanded values of the inverter's real and reactive reference power. The power generated is programmed as a positive number and the power absorbed as a negative number. In particular, if the inverter works with a battery bank connected and we want to charge the battery, the sign of the required real power has to be negative.

Note that switching to STATE 3 requires that the DG be synchronized to the inverter-controlled grid. It does not happen automatically. To synchronize the DG to the grid:

- The voltage magnitudes must be equal.
- The frequency must be same as the grid frequency.
- The phase angles must be equal.

The DG remains unloaded during the synchronization process until the required conditions are met. This, in turn, results in loading or activation of the DG, and the inverter is switched to the slave mode.

Switching to STATE 1 (with the inverter in the master mode and the DG disconnected) happens automatically. However, we must also make the DG ready to become a master when the next switching is commanded. In other words, we keep the DG idling, which is achieved by freezing certain variables.

IV. CASE STUDY

In this case study, we use our standard model of a small wind turbine with a permanent magnet synchronous generator and with furling control. It is connected to the utility through an inverter, which operates in a slave mode. A diesel generator controls the frequency and voltage of the utility. The utility load (village load) is set to be constant. The system considered, shown in Figure 3, is modeled using standard RPM-SIM blocks. The inverter is programmed to operate in the slave mode. In this system, we want to maximize the real power P_{inv} provided by the wind turbine generator to the utility by running the wind turbine at its optimum operating point. Therefore, we set reference reactive power Q_{ref} to zero, resulting in a unity power factor at the line side. We also replace the reference real power of the inverter P_{ref} by choosing a proper set point V_{Dcref} to maintain the DC bus voltage. We compare this value with the actual value of v_{DC}, the input voltage to the inverter. The difference $v_{DC} - V_{DCref}$ controls the q-component i_{qINVs} of the current contributed to the utility by the inverter. This is the only modification of the standard RPM-SIM inverter model.

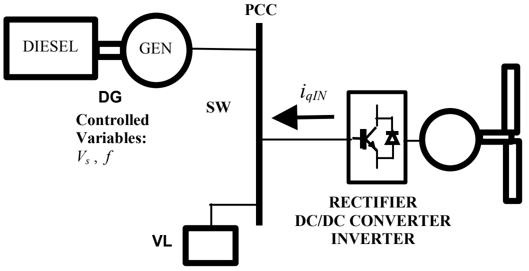

Figure 3. Wind turbine generator connected to the grid with power converter

Figure 4 shows the circuit diagram, which explains the connection between the rectifier and the inverter. In this circuit, we included a DC/DC converter represented by the gain K_{DC} related directly to the duty ratio D. The DC/DC converter enables peak power tracking (PPT).

This DC/DC power converter may be implemented as:

- A buck or step-down converter with $K_{DC} > 1$ and $D = 1/K_{DC}$
- A boost or step-up converter with $0 < K_{DC} < 1$ and $D = 1 - K_{DC}$
- A buck-boost converter with $0 < K_{DC} < 5$ and $D = 1/(K_{DC} + 1)$.

In the system we modeled and simulated, we used a buck-boost converter. The DC/DC converter is controlled to optimize the wind turbine operation by controlling K_{DC}.

The output AC power of the wind turbine generator is

$$P_{AC} = 3V_{ph} I_S$$

$$V_{ph} = \frac{\pi}{3\sqrt{6}} K_{DC} v_{DCref} \, .$$

Then, using the notation introduced in Figure 4, the following equations lead to the determination of the inverter current on the DC side, I_{inv}:

$$I_{DC1} = \frac{P_{AC}}{K_{DC} v_{DC}}$$

$$v_{DC} K_{DC} = \frac{1}{C_I} \int \left(I_{DC1} - \frac{K_{DC} v_{DC}}{R_R} - \frac{I_{DC}}{K_{DC}} \right) dt$$

$$v_{cap} = \frac{1}{C_O} \int (I_{DC} - I_{inv}) dt \qquad I_{inv} = \frac{P_{inv}}{v_{cap}}$$

Requesting the equality of the inverter's input power and the power provided to the utility, we keep the v_{DC} voltage constant. In Figure 3, the capacitor C_i is used to define the voltage $K_{DC} v_{DC}$ and the resistor R_R represents power losses from the electronics. We set $K_{DC} = 1$ if operation without the PPT is required.

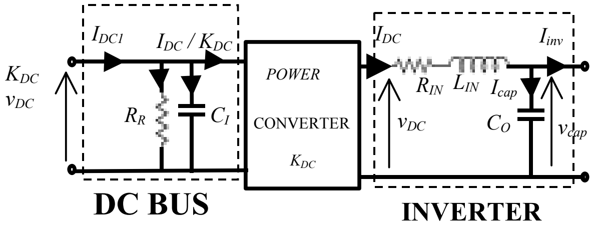

Figure 4. Circuit diagram of the connection between the rectifier and the inverter

In our simulation, we considered the operation of the system in a turbulent wind without the PPT. Figure 5 shows the line voltage and the relative frequency controlled by the diesel generator, illustrates the real power balance, and shows the transients for the inverter input (v_{DC} and I_{DC}) and output (i_{qINVs} and P_{inv}). We can clearly see that when the furling mechanism is activated, the diesel generator makes up for the power deficiency.

V. CONCLUSIONS

In this paper, we briefly presented the RPM-SIM simulator and, in particular, its abilities to simulate and analyze renewable energy systems with power converters. We developed this modular simulation system to study applications and cost-effective performance of renewable energy systems, analyze both static and dynamic performance, develop control strategies, and simulate autonomous renewable energy systems under different generation and load conditions (such as different wind speeds, temperature, insolation conditions, and load profiles).

The power converter is an important part of the power system both for grid-connected and isolated operation. It is apparent that the power converter has the ability to control the wind turbine, balance the energy, and supply good power quality to the power network.

In future work, we will expand the use of the simulator beyond autonomous systems to the level of power system

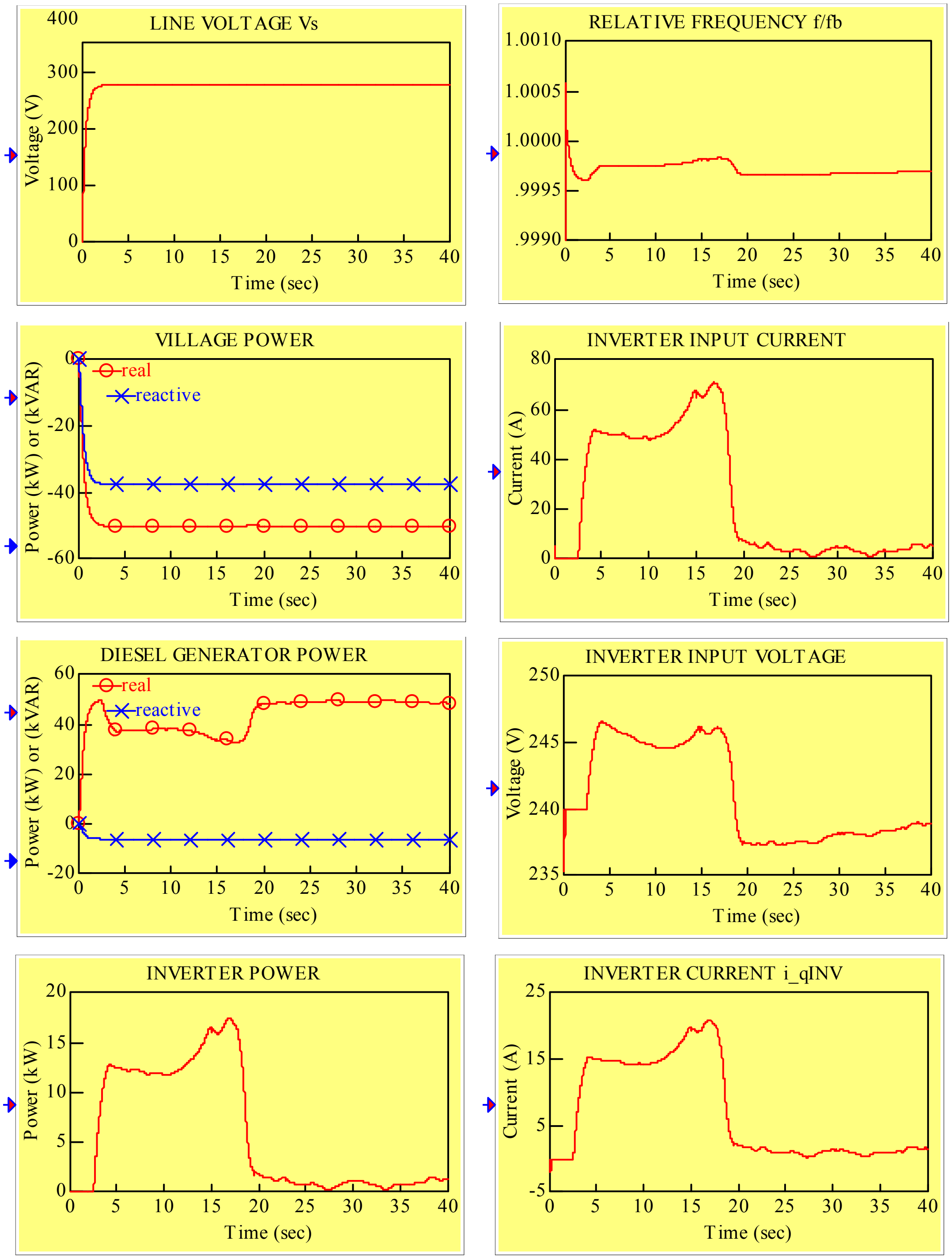

Figure 5. Furling effect on the energy system with two power sources: the DG and the WT generator connected to the utility through the inverter

network modeling. We plan to model a static VAR compensator (SVC) and flexible AC transmission systems (FACTS). We will also append the system with other generating plants, such as steam, hydro, fuel cell, and recently emerging on the market flywheel motor/generator energy storage. RPM-SIM simulator can be obtained by contacting NREL.

VI. ACKNOWLEDGMENTS

We wish to thank Tod Hanley and Peter Huebner from Bergey WindPower Company for providing valuable information data. In addition, we would like to thank NREL for the support in undertaking this project. The U.S. Department of Energy funded this work under contract number DE-AC36-98-GO10337.

VII. REFERENCES

[1] J.T. Bialasiewicz, E. Muljadi, R.G. Nix, and S. Drouilhet, *Renewable Energy Power System Modular Simulator RPM-SIM User's Guide*, NREL Technical Report No. NREL/TP-500-29721. Golden, CO: NREL, March 2001.

[2] J.T. Bialasiewicz, E. Muljadi, S. Drouilhet, and G. Nix, Hybrid power system with diesel and wind turbine generation, *Proc. 1998 American Control Conference*, vol. 3, pp. 1705–1709, 1998.

[3] J.T. Bialasiewicz, E. Muljadi, S. Drouilhet, and G. Nix, Modular simulation of a hybrid power system with diesel and wind turbine generation, *Proc. Windpower '98*, 1998.

[4] E. Muljadi, G. Nix, and J.T. Bialasiewicz, Analysis of the dynamics of a wind turbine water-pumping system, *Proc. IEEE PES 2000 Summer Meeting*, 2000.

[5] W.Q. Jeffries, *Analysis and Modeling of Wind/Diesel Systems Without Storage*, Ph.D. Thesis, Department of Mechanical Engineering, University of Massachusetts, 1994.

[6] A.J. Tsitsovits and L.L Freris, Dynamics of an isolated power system supplied from diesel and wind, *Proc. IEEE*, 130, Part A, No. 9, pp. 587–595, 1983.

[7] J.T.G. Pierik and De Bonte, *Quasi Steady State Simulation of Autonomous Wind Diesel Systems (Status Report)*, Report No. ECN-85-091. Petten, The Netherlands: Energy Research Centre of the Netherlands, May 1985.

[8] M.P. Papadopoulos, et al., Penetration of wind turbines in islands with diesel power stations, *Proc. EWEC 1988*, pp. 512–517, 1988.

[9] K. Uhlen and O. Skarstein, A short term dynamic simulation model for wind/diesel systems, *Proc. 10 BWEA Conference*, pp. 239–242, 1988.

[10] J. F. Manwell, et al., Developments in experimental simulation of wind/diesel systems, *Proc. EWEC 1989*, pp.759–763, 1989.

[11] M. P. Papadopoulos, et al., Simulation of the parallel operation of diesel, wind turbines and photovoltaic systems, *Proc. EWEC 1991*, pp. 495–499, 1991.

[12] P. Lundsager, et al., The JODYMOD dynamic wind diesel simulation program—Part I: Description of the model and its validation, *Proc. BWEA/RAL Workshop on Wind Energy Penetration into Weak Electricity Networks*, pp.133–149, 1993.

[13] H. Binder, The JODYMOD dynamic wind diesel simulation program—Part II: Presentation of the program, demonstration and examples, *Proc. BWEA/RAL Workshop on Wind Energy Penetration into Weak Electricity Networks*, pp. 150–160, 1993.

[14] W.Q. Jeffries, J.G. McGowan, and J.F. Manwell, Development of a dynamic model for no storage wind/diesel systems, *Wind Engineering*, (20):1, pp. 27–38, 1996.

[15] P.D. Ladakakos, et al., Development of a simulation model for investigating the dynamic operation of autonomous wind-diesel systems, *Proc. EWEC*, 1997.

[16] R.H. Park, Two-reaction theory of synchronous machines-generalized method of analysis—Part I, *AIEE Trans*., vol. 48, pp. 716–727, 1929.

[17] H.C. Stanley, An analysis of induction motor, *AIEE Trans*., vol. 57 (supplement), pp. 751–755, 1938.

[18] P.C. Krause and C.H. Thomas, Simulation of symmetrical induction machinery, *IEEE Trans. Power Apparatus and Systems*, vol. 84, pp. 1038–1053.

[19] C.-M., Ong, *Dynamic Simulation of Electric Machinery Using Matlab/Simulink*, Upper Saddle River, NJ: Prentice Hall Professional Technical Reference, 1998.

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
November 2001

3. REPORT TYPE AND DATES COVERED
Conference Paper

4. TITLE AND SUBTITLE
RPM-SIM–Based Analysis of Power Converter Applications in Renewable Energy Systems: Preprint

5. FUNDING NUMBERS
WER1.1710

6. AUTHOR(S)
Jan T. Bialasiewicz, Eduard Muljadi, and R. Gerald Nix

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-500-30563

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This paper briefly presents the RPM-SIM simulator and, in particular, its abilities to simulate and analyze renewable energy systems with power converters. This modular simulation system is used to study applications and cost-effective performance of renewable energy systems, analyze both static and dynamic performance, develop control strategies, and simulate autonomous renewable energy systems under different generation and load conditions (such as different wind speeds, temperature, insolation conditions, and load profiles).

14. SUBJECT TERMS
RPM-SIM; power converter; power conversion; renewable energy

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102