DEVELOPMENT OF A FULL-SCALE-LAB-VALIDATED DYNAMIC SIMULINK© MODEL FOR A STAND-ALONE WIND-POWERED MICROGRID

Nicholas T Janssen and Rorik A Peterson, Ph.D.
Department of Mechanical Engineering
University of Alaska, Fairbanks
306 Tanana Dr, Fairbanks, Alaska 99775
United States
njanssen2@alaska.edu (907) 474-5887
rapeterson@alaska.edu (907) 474-5593

ABSTRACT

Isolated hybrid wind microgrids operate within three distinct modes, depending on the wind resources and the consumer grid demand: diesel-only (DO), wind-diesel (WD) and wind-only (WO). Few successful systems have been shown to consistently and smoothly transition between wind-diesel and wind-only modes. The University of Alaska – Fairbanks Alaska Center for Energy and Power (ACEP) has constructed a full scale test bed of such a system in order to evaluate technologies that facilitate this transition. The test bed is similar in design to the NREL Power Systems Integration Laboratory (PSIL) and sized to represent a typical off-grid community. The objective of the present work is to model the ACEP test bed in DO and WD modes using MATLAB™ SIMULINK© and then validate the model with actual full-scale laboratory measurements. As will be shown, the frequency responses are grouped into three classifications based on their behavior. The model is shown to be successful in describing the frequency response of relatively small (0.15 per unit) steps in load. Modifications to the excitation system model are discussed which could improve the accuracy for larger steps in load. The ACEP test bed and associated SIMULINK© model are to be used in future work to support investigating WO operation.

INTRODUCTION

Many remote communities in the world generate electricity from a central plant powered by diesel electric generators (DEGs). These communities rely on expensive diesel fuel to power their grid. Rising fuel costs are rendering this approach financially unsustainable for many of these communities, which are now looking to use renewable resources, such as wind, to offset these costs. [1]

An islanded microgrid that uses a combination of diesel-electric generation and wind power in order to meet the electrical demand of the consumer is considered a Hybrid Wind Diesel (HWD) system [2]. A HWD system consists of at least one DEG, one or more Wind Turbine Generators (WTGs), and a dynamic consumer load. The system may also make use of an energy storage device (such as a lead-acid battery) and/or dump load. As the ratio of grid demand to wind power approaches unity, the need to dump excess energy to a secondary load becomes necessary in order to avoid motoring the diesel engine. If the DEG can be successfully decoupled from the grid (mechanically or electrically) the system is classified as “high penetration” (or more recently “high contribution”).

High contribution hybrid wind diesel systems (HCHWD) present many control challenges not encountered in larger, more stable electric grids. [3] With no source of base load generation or spinning reserve, the only way to achieve an instantaneous balance of real power generation and consumption with a varying source of wind power is for a secondary load controller to divert energy to a sink. The sink may either be a storage device or a dump load. Furthermore, when the DEG is decoupled from the system, a source of reactive power must be present to excite the WTG(s) and any reactive component of the consumer load.

Existing scientific literature has made some good effort in modelling the dynamics of a HWD system [4-7]. Neither lab
nor field validation measurements were presented in [4] nor [5]. Tomilson et al [6] achieved a reasonable frequency response match with their test bed in DO mode, with no WD results presented. Jeffries [7] developed and validated a non-dimensional model with excellent agreement in both WD and DO modes (1994). However, DEG technology has changed much since the publication of both of these studies.

Furthermore, many publications have since been made that utilize some form of these typical SIMULINK© models [8-13] as a basis for their analysis. These models remain un-validated against the dynamics of full-scale modern hybrid systems, such as ACEP’s PSIL.

ACEP has a full-scale hybrid wind diesel test bed (see Fig. 2) that consists of a 320 kVA diesel electric generator (DEG), an 8-bit 250 kW resistive/inductive load bank, and a 150 HP induction machine driven by a motor/VFD, which represents a WTG. (The test bed also has a 1000 amp-hour lead-acid battery bank and inverter. However, these components were not used in the scope of the present research.)

The goal of the present work is to model the transient response of the ACEP HWD test bed in wind-diesel (WD) and diesel-only (DO) modes and compare the results with laboratory measurements. Future plans include the integration of storage technologies with the intent of exploring wind-only (WO) mode.

MATHEMATICAL MODEL

The key components of the ACEP test bed can be seen in the MATLAB™ SIMULINK© block diagram shown in Fig. 3. They are connected via a common 480V AC bus with voltage, current, real power, and reactive power measurement blocks. For simulations, the load bank model is replaced with a switchable load and breaker so as to introduce step load disturbances to the system. Simulating DO and WD modes requires a mathematical model be defined for four major system components: the diesel engine (DE) and speed governor, the synchronous generator (SG), the SG excitation system, and the induction generator (IG). The load is modeled as a constant-impedance with an ideal three-phase switch for load changes.

Diesel Engine/Governor Model

The DE and electronic speed governor block diagrams are typical of those found in the literature. [4-15] (See Fig. 4) The PID type speed controller integrates the error in shaft angular velocity and forwards the resulting signal to the second-order actuator model introduced by Yeager et al [15]. The engine model is a simple first order transport delay, which represents the mean time for all cylinders to fire and for the resulting torque to develop. Time constants and gains were selected based on the consensus in literature with alterations made after lab measurement validation.

The speed governor on the diesel (electrically-driven, electrically-actuated) has the function of keeping the synchronous machine rotating at a constant angular velocity. The speed of the drive shaft is directly proportional to the frequency of the generator and grid.
The synchronous generator model is available in the MATLAB™ SIMULINK© SimPowerSystems© toolbox and can be broken into two components: mechanical and electrical.

The mechanical portion of the synchronous generator model relates rotor speed ($\omega$) to the inertial constant ($H$), mechanical torque ($T_m$), electrical torque ($T_e$), and damping/windage losses ($F$). This is an expression of the commonly used “swing equation”:

$$\frac{d\omega}{dt} = \frac{1}{2H} \cdot (T_e - T_m - F\omega) \quad (1)$$

The electrical model of the wye-connected salient-pole synchronous machine is given in the two-axis ‘dq’ reference frame. Stator, rotor, and damper winding dynamics are represented (see Fig. 5) in the equivalent circuit.

The exciter (or “Automatic Voltage Regulator [AVR]”) is responsible for controlling current to the rotor field windings, which directly affects the terminal voltage of the generator. The exciter on the ACEP test bed is of the AC brushless type.

The MATLAB™ SIMULINK© exciter block models a DC type exciter, as described in [17] (see Fig. 6). The terminal voltage error is fed through a main regulator with a proportional gain and time constant. A small amount of damping is fed back into the primary summing junction. The resulting DC field voltage sets up an opposing magnetic field between the rotor and stator. Limits are often imposed on the level of excitation in order to protect the machine’s armature windings from overheating.

The induction generator, which represents the WTG, is a three-phase AC squirrel-cage machine and is modelled in MATLAB™ SIMULINK© SimPowerSystems© as follows.

The mechanical model of the squirrel cage IG is exactly the same as that of the SG (see Eq. 1). (It should be noted that the ACEP test bed does not have a wind turbine on the rotor of the IG. The total inertia under consideration in the mechanical model is therefore limited to the sum of the IG and drive motor rotor inertias.)

The electrical model of the three-phase, 60 Hz, wye-connected, squirrel cage IG varies from that of the SG previously presented (see Fig. 7). The two-axis ‘dq’ reference frame is used; however, the field windings are excited internally by slip between the rotating magnetic field and the rotor angular velocities. [16] The following equation relates magnetic flux $\phi$, stator current $i$, and number of pole pairs $p$, to electrical torque $T_e$:

$$T_e = \frac{3}{2} p \cdot (\phi_{ds}i_{qs} - \phi_{qs}i_{ds}) \quad (2)$$
The d/q axis fluxes and induced stator currents are calculated by solution of the equivalent circuit (Fig. 7). These equations are presented in further detail by Krause. [16]

DATA COLLECTION

All three phases of instantaneous bus voltage \( (V_{an}, V_{bn}, \text{and } V_{cn}) \) were measured as well as the phase ‘a’ line currents of the DEG, the WTG, and the load (see Fig. 3). Lab measurements were performed on the ACEP HWD test bed in order to verify the mathematical model developed herein. The brief 3-4 second transient periods following various system disturbances were recorded and compared to model predictions. Of primary interest were frequency and power factor calculations were made by interpolating zero-crossings of the phase voltage and line current waveforms. This allowed the mechanical response of the machine \( (\omega) \) to be presented on a time scale, throughout the duration of the transient. RMS values were calculated with a sliding window of 600 data points (0.10 sec, or about 6 cycles).

RESULTS

Data Processing

Measured instantaneous voltages and currents were used to calculate RMS voltages, RMS line currents, frequency \( (f) \), power factor \( (PF) \), real power \( (P) \), reactive power \( (Q) \), and impedance \( (Z) \). Frequency and power factor calculations were made by interpolating zero-crossings of the phase voltage and line current waveforms. This allowed the mechanical response of the machine \( (\omega) \) to be presented on a time scale, throughout the duration of the transient. RMS values were calculated with a sliding window of 600 data points (0.10 sec, or about 6 cycles).

Diesel Only (DO) Mode – Laboratory Results

In DO mode, the WTG is electrically isolated from the system and the DEG takes 100% of the dynamic consumer load. Load steps of various magnitudes were performed at multiple power factors (PF) as well as at various DEG loading levels.

Initial observations show three distinct responses whose shapes depend primarily on the size of the load step (see Fig. 8). Large steps (0.80 per unit) up or down (Figs. 8a and 8d) in load and medium steps (0.40 per unit) down (Fig. 8e) in load result in “type 1” responses, which exhibit a linear recovery region before settling out to steady state. Medium steps (about 0.40 per unit) up in load (Fig. 8b) result in a distinct shape that oscillates essentially undamped at a frequency of about 2.3 Hz for no more than 3 seconds before sharply attenuating (type 2). Smaller steps (0.15 per unit) result in small, single oscillations, termed here as “type 3” responses (Figs. 8c and 8f). Good repeatability was observed in replicated experiments.

Diesel Only (DO) Mode – Simulation Results

Model parameters were chosen to provide the best results over the range of inputs tested without significant deviation from nominal values. The results of the computer simulation are shown concurrently with their respective measured data from the laboratory experiment (Figs. 8-13).

The simulation results of type 1 and 2 perturbations differ in shape significantly from those measured on the test bed. However, the magnitudes of the frequency excursions in the simulation are in error by no more than 1.1%. The model also significantly overestimates the settling time for medium to large steps down in load. Small (type 3) steps appear to be well predicted by the model.

Figures 9 and 10 show a collection of type 3 responses (steps of about 0.15 per unit) of the system in diesel-only mode. Good agreement with measured results is seen under moderate to heavy load across a range of power factors. Frequency deviations under low load are over-predicted by the model, but have the same general shape.

Wind-Diesel (WD) Mode

In WD mode, the IG is brought up to synchronous speed and electrically connected to the bus. The first set of design points were taken with the IG connected but under no drive motor torque (see Figs. 11) in order to simulate light wind. Then, with the IG connected and under torque from the drive motor, two cases were considered: steps in load under constant wind power (Fig. 12) and steps in wind power under constant load (Fig. 13).

General observations of model accuracy indicate good results at higher levels of DEG loading and with smaller perturbations. The frequency of oscillations in Figures 11 and 12 are well-predicted by the model, as are the magnitudes in Figures 11-13.
CONCLUSIONS

Mathematical models of the major components of a HCHWD system were developed and compared with full-scale laboratory measurements in DO and WD modes. Three distinct frequency response shapes were observed based on the magnitude and direction of the disturbance in consumer load. The mathematical model gives good results at moderate to high levels of DEG loading and relatively small disturbances. The results presented herein represent the best arrangement of the numerous machine parameters needed to fully define the model. It is clear that significant improvements need to be made to the structure of the model in some places, depending on its intended end-use.

1. The DEG speed controller may use adaptive tuning in order to set the P, I, and D gains on-the-fly.
2. The model of the AVR presented here is highly simplified.

Implementation of a “discontinuous” type exciter as described in [17] may improve the accuracy of the model. This type of AVR deliberately boosts the level of excitation current immediately following a system fault. This has the effect of increasing terminal voltage and air gap power, which assist in deceleration of the unit. However, it is beyond the scope of this research to reverse engineer the specific DEG controller and AVR design used by the equipment in the test laboratory.

Future work

In order to develop a reliable means of transitioning into WO mode, additional technologies will need to be investigated. The Alaska Center for Energy and Power (ACEP) is currently in the process of procuring a power electronic rectifier/inverter capable of fulfilling the role of frequency and voltage regulator in WO mode. Integration of this inverter into the ACEP HWD test bed is planned for 2014. Further advancement of the model presented herein may be of value to this initiative, but would require knowledge of the proprietary software within the DEG’s digital AVR.
Figure 9 - DO mode laboratory and simulation response characteristics, unity power factor

Figure 10 - DO mode laboratory and simulation response characteristics, 0.80 lagging power factor. (Heavy load not tested.)
Figure 11 – WD mode laboratory and simulation results. IM connected, but under no drive torque.

Figure 12 - WD mode laboratory and simulation results. IM connected steady drive torque (strong wind).

Figure 13 - WD mode laboratory and simulation results. Steady 0.80 PF lagging load, steps in wind power.
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Marc Mueller-Stoffels, PhD
Research Assistant Professor
Power Systems Integration Program Director
Alaska Center for Energy and Power
Institute of Northern Engineering
University of Alaska Fairbanks

David Light
Research Engineer
Alaska Center for Energy and Power
Institute of Northern Engineering
University of Alaska Fairbanks

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