

Improved Frequency Regulation in Mini-Grids with High Wind Contribution using Online Genetic Algorithm for PID Tuning

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Abstract—Mini-grids with high wind contribution tend to be relatively more dynamic and less stable than wind integration in large interconnected grids. This instability is primarily due to frequency fluctuations introduced from highly variable wind generation, multiple single-phase distribution branches with highly unbalanced single-phase loads, large pseudo-instantaneous changes in load, over compensation of reactive power, and lower machine inertias providing less damping. The objective of this research is to investigate the use of a genetic algorithm (GA) based proportional integral derivative (PID) diesel speed controller to improve frequency regulation in standalone high contribution wind-diesel mini-grid systems. A dynamic model of a standalone high contribution wind-diesel system was developed to study frequency regulation under variable wind and load conditions. The results using GA-based PID diesel speed control demonstrate improved frequency regulation as compared to standard diesel speed controls.

Index Terms—Diesel driven generators, Frequency regulation, Genetic algorithms, Voltage stability and Wind power generation.

I. INTRODUCTION

The ever rising demand for clean electrical energy in the modern world has led to several initiatives for extensive research into the integration of renewable energy sources such as wind turbine generators into the existing electric grid. This is especially true in the case of small wind turbine (SWT) integration in the range of 10-300 kW. In 2009 about 34.4 MW of SWTs installed were grid-tied, while 7.6 MW were off-grid systems [1]. In the last decade several advancements have been made in the field of wind power controls to improve system stability when wind energy systems are integrated into conventional grids [2-9]. However, considerably less focus has been placed on the stability of mini-grids with medium to high contribution hybrid wind systems, specifically voltage stability and frequency regulation [9-15].

Standalone medium to high contribution hybrid wind systems are most commonly found in isolated communities with limited or no access to a main electrical grid intertie. Such systems are found in developing countries, remote island communities, and other remote regions around the world. For example, over 250 remote communities in Alaska have no access to the main electric utility intertie and their only source

of power is diesel electric generators (DEGs) [16]. Due to the rise in the cost of fuel and state and federal renewable energy initiatives, a number of these communities are planning to integrate medium to high contribution wind into their existing DEG systems [17]. The typical structure in these mini-grid systems is a wind farm integrated into the existing DEG plant bus through a short 3-phase ac distribution line with loads served via a number of short single-phase ac distribution lines. Highly unbalanced loading, combined with highly variable wind generation, overcompensation of reactive power for induction wind generator excitation, and lower machine inertias contribute to the system instability.

The goal of this research is to investigate the application of genetic algorithm (GA) based proportional integral derivative (PID) diesel speed control for improved frequency regulation in wind-diesel mini-grids with high wind contribution using a dynamic system model. The application of GAs in power system operations has been studied over the last few decades, including optimized control and distribution strategies [18-20]. Our model is based on typical wind-diesel mini-grid installations with a wind farm connected to the main distribution bus via a short transmission line with a secondary load controller to compensate for frequency changes due to wind speed. The model is used to demonstrate improved frequency regulation for a wind-diesel mini-grid with high wind contribution using GA based PID diesel speed controls in place of standard PD speed control under variable wind and load conditions.

II. STANDALONE WIND-DIESEL DYNAMIC MODEL DEVELOPMENT

The wind-diesel dynamic system model of an isolated community shown in Fig. 1 was developed in MATLAB[®] Simulink[®]. The system consists of six wind turbine generators each rated to produce 110 kWe at a wind speed of 16 m/s tied to a diesel electric generator (DEG) plant consisting of two 475 kWe, 1800 RPM, three-phase, 480 VAC, 60 Hz DEGs with a three-phase distribution feeder.

A. DEG Model

The DEGs are modeled as 4-pole synchronous generators with a diesel engine speed governor and generator voltage controller based on an existing model in a MATLAB[®] Simulink[®] SimPowerSystems blockset as shown in Fig. 2.

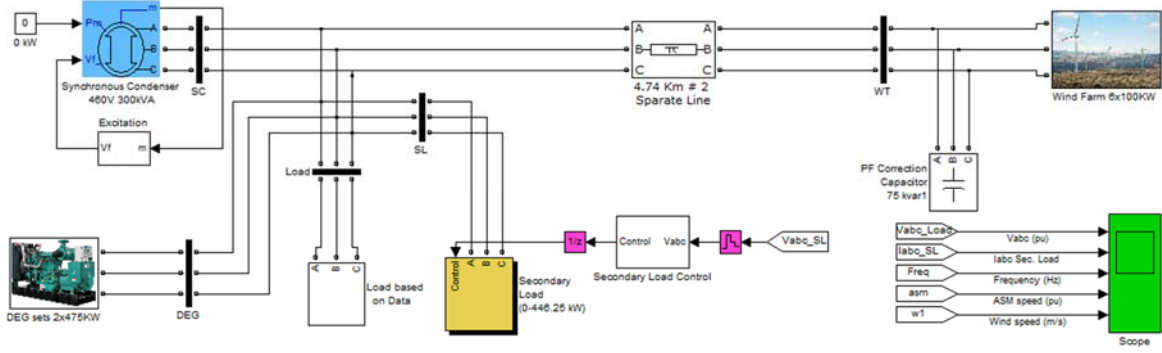


Fig. 1. Dynamic model of standalone wind-diesel system.

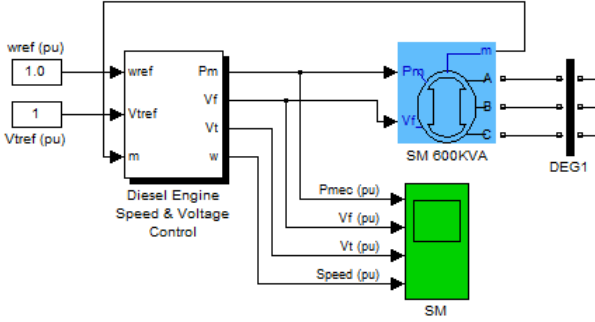


Fig. 2. DEG model with diesel engine speed and generator voltage control.

The diesel engine is modeled as a speed governor with desired and actual speed as the inputs and mechanical power and field voltage as the outputs. The synchronous generator is modeled as an IEEE Type 1 two axis dq salient pole machine with a voltage regulator combined with an exciter. The inputs to the synchronous machine model are the mechanical power and field voltage output of the Diesel Engine Speed & Voltage Control block. The outputs of the synchronous machine are the rotor speed and three-phase voltages for feedback to the speed governor and exciter, respectively. The inertia of the diesel engine and synchronous generator are combined in determining the mechanical shaft power output.

The Diesel Engine Speed and Voltage Control block consists of a PD speed control driving the actuator for the speed governor, and a separate voltage control system. The transfer functions for the PD speed controller $G_{PD}(s)$ and the actuator $G_A(s)$ are

$$G_{PD}(s) = \frac{1+T_3.s}{1+T_1.s+T_1.T_2.s^2} \quad (1)$$

where T_1 , T_2 , and T_3 are the speed controller time constants, and

$$G_A(s) = \frac{1+T_4.s}{s(1+T_5.s)(1+T_6.s)} \quad (2)$$

where T_4 , T_5 , and T_6 are the actuator time constants. The reaction time of the diesel engine to the changes in rotor speed is considered as a simple time delay T_d .

In this work the PD speed controllers on the diesel generator sets are replaced by a GA-based PID controller to minimize the steady state error in order to improve the frequency regulation of the system. The transfer function for the GA-based PID controller is

$$G_{PID}(s) = \frac{T_9.s^2+(1+T_7)s+T_8}{T_8+T_7.S+T_9.S^2} \quad (3)$$

where T_7 , T_8 , and T_9 are the speed controller time constants.

The speed controller time constants are adjusted using the GA discussed in section III.

B. Wind Turbine Induction Generator Model

The wind turbine induction generators are modeled as pitch controlled machines with induction machines based on an existing model in the MATLAB[®] Simulink[®] SimPowerSystems blockset as shown in Fig. 3.

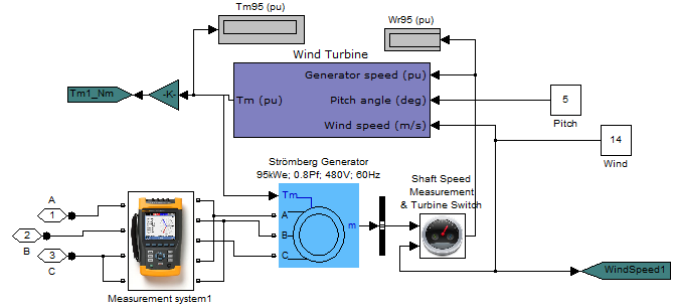


Fig. 3. Wind turbine induction generator model.

The wind turbine is modeled based on a variable pitch system. The performance coefficient C_p of the turbine is modeled as a function of wind speed, rotational speed, and pitch angle (β). The maximum value of C_p occurs at a pitch angle of zero degrees ($\beta = 0$). The wind turbine model inputs are the generator speed in per unit based on the synchronous speed, blade pitch angle (β), and wind speed.

The per unit mechanical output power $P_{M,pu}$ of the wind turbine is defined in [21] as

$$P_{M,pu} = k_p C_{p,pu}(\lambda, \beta) v_{wind,pu}^3 \quad (4)$$

where k_p is the power gain for $C_{p,pu} = 1$ and $v_{wind,pu} = 1$, λ is the tip speed ratio, β is the pitch angle in degrees, and $v_{wind,pu}$ is the per unit wind speed.

The tip speed ratio λ is defined in [21] as

$$\lambda = \frac{\omega_r \cdot r}{v_{wind}} \quad (5)$$

where ω_r is the rotor angular speed in rad/s, r is the radius of rotor in m, and v_{wind} is the wind speed in m/s.

The wind turbine model output is per unit mechanical torque $T_{M,pu}$ applied to the shaft of the induction generator calculated as

$$T_{M,pu} = \frac{P_{M,pu}}{\omega_{r,pu}} \quad (6)$$

where $P_{M,pu}$ is the per unit mechanical power in (4) and $\omega_{r,pu}$ is the per unit rotor angular velocity.

The induction generator is modeled as a three-phase wye-connected asynchronous machine with a squirrel cage rotor using a dq rotor reference frame. The dq voltage equations for the induction generator are defined in [22] as

$$V_{qs} = r_s i_{qs} + \omega \lambda_{ds} + \frac{d}{dt} (\lambda_{qs}) \quad (7)$$

$$V_{ds} = r_s i_{ds} - \omega \lambda_{qs} + \frac{d}{dt} (\lambda_{ds}) \quad (8)$$

where r_s is the resistance of the stator, i_{ds} and i_{qs} are the d and q axis currents in the stator, respectively, λ_{ds} and λ_{qs} are the d and q axis flux linkages, respectively, and ω is the electrical angular velocity of the arbitrary reference frame.

The induction generator input is the mechanical torque $T_{M,pu}$ applied to the shaft in per unit based on the generator ratings. The electromagnetic torque T_e of the generator expressed in terms of the arbitrary reference variables is [22]

$$T_e = \left(\frac{3}{2} \right) \left(\frac{P}{2} \right) L_M (i_{ds}' i_{qr}' - i_{qs}' i_{dr}') \quad (9)$$

where P is the total number of poles, L_M is the magnetizing inductance, and i_{dr}' and i_{qr}' are the d and q axis rotor currents referred to the stator, respectively. The mechanical drive torque T_M in N-m and rotor angular velocity ω_r in rad/s of the generator are related by the electromagnetic torque T_e as [22]

$$T_M = J \left(\frac{2}{P} \right) \frac{d}{dt} (\omega_r) + T_e \quad (10)$$

where J is the rotor inertia in kg-m². The turbine inertia is added to the generator inertia in this model.

The generator outputs are the three-phase voltages and rotor speed for feedback to the wind turbine pitch control. Impedance controllers are used on the output of the induction generators to provide voltage and frequency control. Capacitor banks are used on the output of each wind turbine induction generator to provide excitation to the rotor.

C. Distribution System

The distribution system is modeled as a 4.7 km three-phase transmission line using a distributed parameter π -model as shown in Fig. 1. The transmission line used for the current scenario is #2 ACSR Sparate. The system consists of a dynamic load based on load data from an actual system.

D. Secondary Load Controller

The system also includes a state-based secondary load controller that responds to ± 0.5 Hz deviations in frequency by adding or removing incremental load to regulate the frequency given variations in wind speed, therefore, wind power output.

III. GENETIC ALGORITHM (GA) BASED CONTROL

A GA-based PID diesel speed controller with the transfer function in (3) replaced the standard PD speed controller. The GA-based PID diesel speed controller functions to improve the frequency regulation of the system under variable wind generation and load conditions. The GA adjusts the PID controller time constants to minimize frequency deviation Δf . In this application the input to the GA control is the Δf at the load bus which needs to be regulated at ± 0.1 Hz.

The GA uses a ranking selection function based on normalized distribution with arithmetic crossover and mutates based on uniform probability distribution. The GA initializes the population which is based on floating point representation and provides a ranking based on the fitness function which is the least mean square error of the step response for Δf .

Ranked individuals are selected using a normalized geometric ranking based on the probability of an individual being selected P_i which is defined in [23] as

$$P_i = q^r (1 - q)^{r-1} \quad (10)$$

where q is the probability of selecting the best individual i , r is the rank of the individual with 1 as best, and q' is defined as

$$q' = \frac{q}{1 - (1 - q)^P} \quad (11)$$

with P as the population size.

The GA uses arithmetic crossover in which the new generation is based on crossover to create the next generation defined in [24] as

$$\text{Offspring1} = (a)\text{Parent1} + (1-a)\text{Parent2} \quad (12)$$

$$\text{Offspring2} = (1-a)\text{Parent1} + (a)\text{Parent2} \quad (13)$$

where a is a random weighting factor chosen before each crossover operation.

A uniform mutation algorithm is used with 0.08% mutation probability. The selected gene value in the next generation is replaced with a random value in the bounds specified. The GA updates the PID controller time constants at a set interval and ends at the set maximum generations.

IV. SIMULATION CASES

The wind-diesel model is used to observe load frequency deviations under variable wind and load conditions without and with GA-based PID diesel speed control using the ODE23tb solver. The state-based secondary load controller is set to regulate the frequency at ± 0.5 Hz. Identical wind speeds are applied to all wind turbines at the same time.

Plots of load bus frequency, wind bus voltage and speed, and secondary load voltage and current without and with GA-based PID diesel speed control are presented in Figs. 4(a-b) for a mean wind speed of 11.9 m/s. Zoomed in portions (see boxes in Fig. 4) of load bus frequency and wind bus voltage are shown in Fig. 5. The first 40 seconds of data was omitted to remove startup dynamics in both cases.

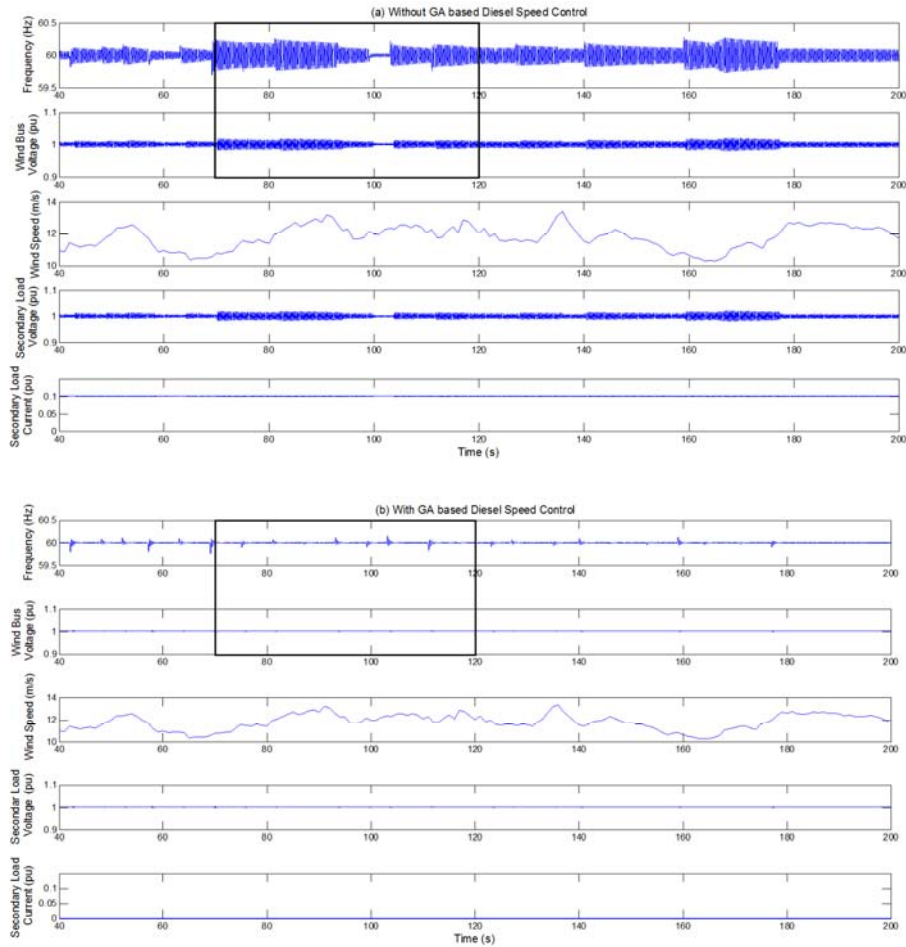


Fig. 4. Plots of load bus frequency, wind bus voltage and speed, secondary load voltage and current (a) without and (b) with GA-based PID diesel speed control.

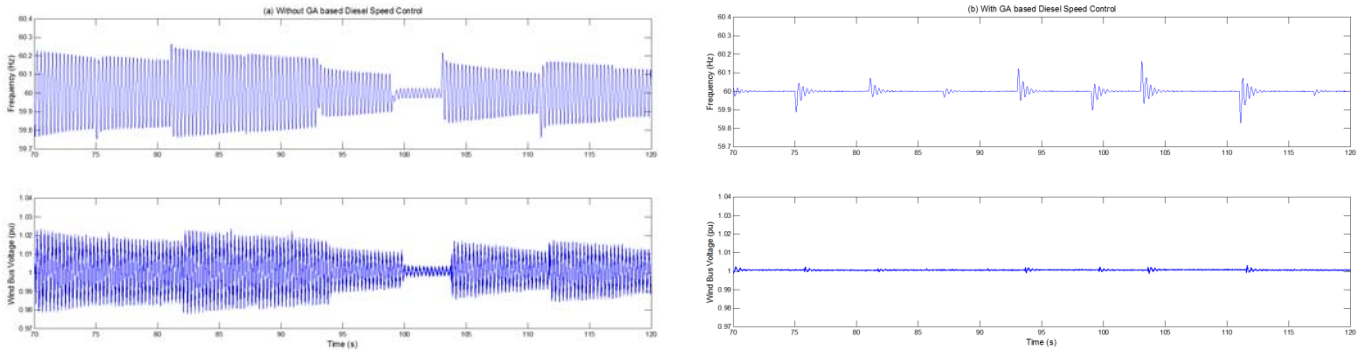


Fig. 5. Plots of load bus frequency and wind bus voltage (a) without and (b) with GA-based PID diesel speed control.

V. DISCUSSION OF RESULTS

The results of the simulations in Figs. 4-5 demonstrate improved frequency regulation using GA-based PID diesel speed control with variable wind and load conditions.

A. Without GA-Based PID Diesel Speed Control

The plot of load bus frequency without GA-based diesel speed control (1st plot of Figs. 4(a) and 5(a)) shows a frequency range of 59.75 to 60.25 Hz. The short time oscillations in load frequency corresponding to changes in wind speed (3rd plot of Fig. 4(a)) are not well damped, therefore, the diesel speed control is lagging behind in compensation. As the wind speed

decreases or increases a corresponding droop or rise in frequency is observed.

The voltage at the wind bus (2nd plot of Figs. 4(a) and 5(a)) is also observed for verification of response to changes in wind speed. The voltage range of 0.98 to 1.02 pu is within limits, but would contribute to voltage flicker. The plots of per unit secondary load voltage and current (4th and 5th plot of Fig. 4(a)) illustrate that the secondary load control (not GA-based) reacts by increasing the secondary load current in the system to regulate the system frequency with the decrease or increase in contribution of wind power. This decreases the system efficiency as electricity is lost to heat in the secondary load.

B. With GA-Based PID Diesel Speed Control

The plot of load bus frequency with GA-based PID diesel speed control (1st plot of Figs. 4(b) and 5(b)) shows a frequency range of 59.85 to 60.15 Hz. The short time oscillations in load frequency and per unit wind bus voltage corresponding to changes in wind speed (third plot of Fig. 4(b)) are more damped as compared with standard diesel speed control.

The plot of per unit wind bus voltage (2nd plot of Figs. 4(b) and 5(b)) with minimal wind bus voltage fluctuations (0.999-1.001 pu) shows that improved frequency regulation with GA-based PID diesel speed control also has a favorable impact on the wind bus voltage. This is primarily due to reduced power (current) swings between the wind, and diesel and load busses over the transmission line. The plots of per unit secondary load voltage and current (4th and 5th plot of Fig. 4(b)) illustrate that the load bus frequency with changing wind speeds is regulated solely by the GA-based PID diesel speed controller, eliminating the need for secondary load control.

C. Sensitivity to Average Wind Speed (Statistical Analysis)

A statistical analysis (see Table 1) of the load frequency and wind bus voltage deviation was performed using five data sets of equal length, but with different mean wind speeds.

TABLE 1: STATISTICS OF LOAD FREQUENCY AND WIND BUS VOLTAGE DEVIATIONS FOR MEAN WIND SPEEDS WITHOUT AND WITH GA CONTROL

Mean Wind Speed (m/s)	Load Frequency Deviation				Wind Bus Voltage Deviation			
	Mean (Hz)		STD (Hz)		Mean (Vrms)		STD (Vrms)	
	w/o GA	GA	w/o GA	GA	w/o GA	GA	w/o GA	GA
6.6	0.185	0.021	0.121	0.019	5.52	0.782	0.810	0.156
9.2	0.177	0.024	0.113	0.022	5.77	0.598	0.851	0.166
11.9	0.169	0.023	0.107	0.021	5.20	0.736	0.777	0.148
14.2	0.127	0.014	0.084	0.009	4.22	0.524	0.626	0.121
17.8	0.267	0.024	0.197	0.021	5.93	0.756	0.886	0.171

Mean and standard deviations of frequency and wind bus voltage with GA-based PID diesel speed control are an order of magnitude lower than with PD diesel speed control. Minimum deviation occurs for a mean wind speed of 14.2 m/s (near rated WTG output) with GA-based PID diesel speed control improving regulation at this ‘optimal’ grid stability point.

VI. CONCLUSION

A genetic algorithm (GA) based PID diesel speed control strategy is proposed to improve frequency regulation in a standalone high contribution wind-diesel mini-grid. The results of the simulations using the dynamic wind-diesel system model demonstrate improved frequency regulation under transient wind conditions using the proposed control strategy. Further work will involve the development of GA-based WTG, secondary load and distributed control strategies to improve frequency regulation in mini-grids with high wind contribution.

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REFERENCES

[1] P. Zhang, et al., (2012, Mar.). Small Wind World Report Summary, World Wind Energy Association, [Online]. Available: <http://www.wwindea.org/webimages/WWEA%20Small%20Wind%20World%20Report%20Summary%202012.pdf>.

[2] B. Rawn and P. W. Lehn, “A method for assessing stability of wind turbines providing grid frequency stabilization,” *Nordic Wind Power Conference 2009*, September 10-11, 2009.

[3] A. D. Hansen, P. Sorensen, F. Blaabjerg and J. Becho, “Dynamic modeling of wind farm grid interaction,” *Wind Engineering*, vol. 26, no. 4, pp. 191-208, 2002.

[4] G. Lalor, A. Mullane, and M. O'Malley, “Frequency control and wind turbine technologies,” *Power Systems, IEEE Transactions on*, vol. 20, no. 4, pp. 1905- 1913, November 2005.

[5] G. Tarnowski, P. Kjaer, P. Sorensen, and J. Østergard, “Study on variable speed wind turbines capability for frequency response,” in *Proc. 2009 European Wind Energy Conference*, pp. 190-193.

[6] J. G. Sloopweg, H. Polinder, W. L. Kling, and J. A. Ferreira, “Representing wind turbine electrical generating systems in fundamental frequency simulation,” *Energy Conversion, IEEE Transactions on*, vol. 18, no. 4, pp. 516-524, December 2003.

[7] E. Vittal, J. D. McCalley, V. Ajarapu, and T. Harbour, “Wind penetration limited by thermal constraints and frequency stability,” in *Proc. 2007 North American Power Symposium (39th)*, pp. 353-359.

[8] B. G. Rawn, M. Gibescu, W. L. Kling, “A static analysis method to determine the availability of kinetic energy from wind turbines,” *Proc. 2010 IEEE Power & Energy Society Meeting*, pp.1-8.

[9] G. Tarnowski, P. Kjar, P. Sorensen, and J. Ostergaard, “Variable speed wind turbines capability for temporary over-production,” *Proc. 2009 IEEE Power & Energy Society Meeting*, pp. 1-7.

[10] R. Sebastian and R. Pena, “Simulation of a high penetration wind diesel system with a Ni-Cd battery energy storage,” *Proc. 2009 IEEE Industrial Electronics Conference*, pp. 4589-4594.

[11] S. Drouilhet, “Performance and Economic Analysis of the Addition of Wind Power to the Diesel Electric Generating Plant at Wales, Alaska”, *Preliminary Report, National Wind Technology Center*, National Renewable Energy Laboratory, Golden, CO, 1997.

[12] S. Drouilhet, “Power Flow Management in a High Penetration Wind-Diesel Hybrid Power System with Short-Term Energy Storage,” *Preliminary Manuscript, National Wind Technology Center*, National Renewable Energy Laboratory, Golden, CO, 2001.

[13] S. Drouilhet, “Diesel Dispatch Strategies in High Penetration Wind-Diesel Power Systems,” *Presentation to the American Society of Mechanical Engineers, National Wind Technology Center*, National Renewable Energy Laboratory, Golden, CO, 2001.

[14] S. Drouilhet, “Preparing an Existing Diesel Power Plant for a Wind Hybrid Retrofit: Lessons Learned in Wales, Alaska, Wind-Diesel Hybrid Project,” *Windpower 2001 Conference*, Washington, D.C., NREL/CP-500-30586.

[15] R. W. Wies, R. A. Johnson, and A. N. Agrawal, “Life Cycle Cost Analysis and Environmental Impacts of Integrating Wind-Turbine Generators (WTGs) into Standalone Hybrid Power Systems,” *Systems, WSEAS Transaction on*, vol. 4, no. 9, pp. 1383-1393, September 2005.

[16] J. Gay, “Budget crunch burdens villages,” *Anchorage Daily News*, [Online]. Available: <http://commerce.alaska.gov/pub/RuralCuts.pdf>.

[17] Denali Commission, Memorandum of Agreement Re Sustainability of Rural Power Systems, *A Memorandum of Agreement between the Denali Commission, the Alaska Energy Authority and the Regulatory Commission of Alaska*, August 2003.

[18] N. Sinha, R. Chakrabarti, and P. Chattopadhyay, “Evolutionary programming techniques for economic load dispatch,” *Evolutionary Computation, IEEE Transactions on*, vol. 7, no. 1, pp. 83- 94, February 2003.

[19] X. Ma and R. Liu, “Reactive power optimization in power system based on improved niche genetic algorithm,” *Computer Design and Applications (ICDDA), 2010 International Conference on*, vol. 3, pp. 413-416.

[20] A. H. Ahmad and A. A. Abdelqader, “Power system stabilizer design using real-coded genetic algorithm,” *Control, Instrumentation and Automation (ICCLA), 2011 2nd International Conference on*, pp. 25-31.

[21] R. Hunter and G. Elliot, “Wind-Diesel Systems: A Guide to the Technology and its Implementation,” New York: Cambridge University Press, 1994, p. 170.

[22] P. C. Krause, O. Wasynczuk & S. D. Sudhoff, “Analysis of Electric Machinery and Drive Systems,” IEEE Press, 2002, pp. 109-190.

[23] J. A. Joines, C. R. Houck, and M. G. Kay, “A genetic algorithm for function optimization: A MATLAB implementation.” URL: <http://www.ie.ncsu.edu/mirage/GAToolBox/gaot/T> (1996).

[24] S. N. Sivanandam and S. N. Deepa, *Introduction to Genetic Algorithms*, Springer, 2008.