Analysis Of Hybrid Power System Incorporating Squirrel Cage Induction Generators

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Abstract: - This paper presents generic model of hybrid power system consisting in a combined solution one wind turbine with asynchronous generator and on hydro generator with synchronous machine. This technology was developed by to reduce the cost of supplying electricity in remote communities. The optimal wind penetration (installed wind capacity/peak electrical demand) for this system depends on the site availability of hydro energy and available wind resource. The optimal solution is evaluated first using HOMER – special design software for optimizing cost exploitation for a hybrid power systems. For the optimum solution we analyze the system by means of simulation in order to present the system behavior during normal operation.

Key-Words: - Renewable energy, Asynchronous generator, Variable speed generation, Voltage and frequency controller, Homer, Water flow, Optimal design

1. Introduction

Energy is stored in nature in quite a few forms such as: fossil fuels (coal, petroleum, natural gas), solar radiation, in tidal, geothermal and nuclear forms. Energy is not stored in nature in electrical form. However electric energy is easy to transmit at long distances and complies with customer's needs by adequate control [1], [2], [3].

Alternative energy sources are to be used more and more, with fossil fuel used slightly less gradually, and more efficiently. Wind energy conversion is becoming cost-competitive while it is widespread and it has limited environmental impact. Unfortunately its output is not steady and thus very few energy consumers rely solely on wind to meet their electric energy demands. As in general the electric power plants are connected in local or regional power grids with regulated voltage and frequency, connecting large wind generator parks to them may produce severe transients that have to be taken care of by sophisticated control systems with energy storage elements in most cases [1], [4], [5].

Only less than 10% of the total hydro power capacity of the world is used today because many regions with greatest potential have economic problems. However, as energy costs from water are low, resources are renewable and with limited ecological impact. Despite of initial high cost, hydropower is up for a new surge [1], [6].

Variable speed constant voltage and frequency generators with decupled active and reactive power control would make the power grids naturally more stable and more flexible. Electric generators should work at variable speed but provide constant voltage and frequency output via power electronics with full or partial power ratings, to tape more energy from renewable and provide faster and safer reactive power control. Most variable speed generators with bidirectional power electronics control, will also allow motoring operation both in conventional or distributed power grids and in stand-alone applications [1], [7], [8].

In this paper we consider a hybrid power system solution consisting in the integration of wind and hydro diesel variable speed power generation with asynchronous generators operating in grid connection or isolated network operation.

2. Generators Used For Variable Speed Production Of Energy

Based on the prime mover, namely high speed steam or gas turbines, diesel engines, wind turbines and hydraulic turbines, there are several different electrical machine technologies that are suitable generator candidates. The criteria commonly used to compare different electrical machine technologies is that of power or torque density.

Since power density is directly linked to rotational speed, it makes for an unfair comparison of the machines with different rated speed. On the other hand, torque density is independent of rotational speed [9], [10].

Usually for low powers squirrel cage asynchronous generators can be used or other configurations like permanent synchronous generators with radial or axial flux (figure 1). For higher powers frequently doubly fed asynchronous DFIG (figure 2) or synchronous generators can be used SG.

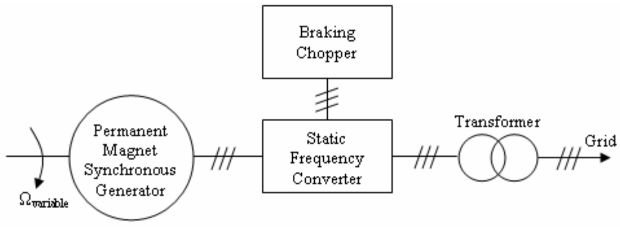

Fig. 1 Permanent magnet synchronous generator with grid connection

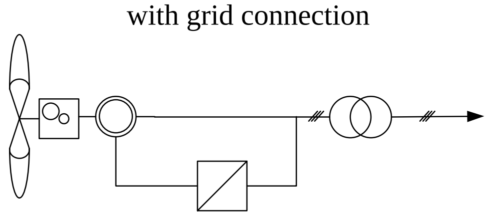

Fig. 2 Doubly fed induction generator with grid connection

Thus, this paper will consider asynchronous generators based solutions.

By self-excited asynchronous generators (SEAG) we mean cage-rotor asynchronous machines with shunt (and series) capacitors may be varied through power electronics (or step-wise). SEAGs may be built with single phase or three phase output and may supply AC loads or AC rectified (DC) autonomous loads. We also include here SEAG s connected to the power grid through soft-starters or resistors and having capacitors at their terminals for power factor compensation (or voltage stabilization) [1], [11].

Wound-rotor asynchronous machines are provided with three phase windings on the rotor and the stator. They may be supplied with energy at both rotor and stator terminals. Both motoring and generating operation modes are feasible, provided the power electronics converter that supplies the rotor circuits via slip-rings and brushes is capable to handle power in both directions. In generator mode the DFIG provides constant (or controlled) voltage V_s and frequency f_1 power through the stator, while the rotor is supplied through a static power converter at variable voltage V_r and frequency f_2. The rotor circuit may absorb or deliver power. As the number of poles of both stator and rotor windings ($2p_1$) is the same, at steady state, according to the frequency theorem, the speed ω_m is:

$$\omega_m = \omega_1 \pm \omega_2 , \quad (1)$$

$$\omega_m = \Omega_R p_1 , \quad (2)$$

where ω_1 and ω_2 are pulsation in stator and rotor, and Ω_R is the mechanical rotor speed.

The sign is "+" in (1) when the phase sequence in the rotor is the same as in the stator and

$$\omega_m < \omega_1 , \quad (3)$$

that is subsynchronous operation. The sign "-" in corresponds to an inverse phase sequence in the rotor when

$$\omega_m > \omega_1 , \quad (4)$$

that is supersynchronous operation.

For constant frequency output, the rotor frequency ω_2 has to be modified in step with the speed variation. This way variable speed at constant frequency (and voltage) may be maintained by controlling the voltage, frequency and phase sequence in the rotor circuit [1], [12]:

$$\omega_2 = \omega_1 - \omega_m . \quad (5)$$

3. Optimal Hybrid System Configuration Evaluation Using HOMER/NREL software

In the present paper we consider the case of one isolated grid powered initially by a single generator In order to identify the best cost/ efficiency combination of resources we have considered the hybrid system consisting in one wind turbine and one hydro that can be added to existing system. This hybrid power system shows how a micro-hydro system competes with wind and diesel power in a stand-alone application figure 3.

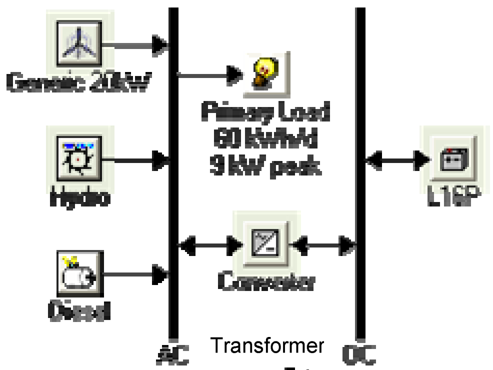

Fig. 3 Hybrid power system model

The powers system is a 60kwh/day isolated load. The daily profile of the load is presented in figure 4 with maximum peak value of 40 kW.

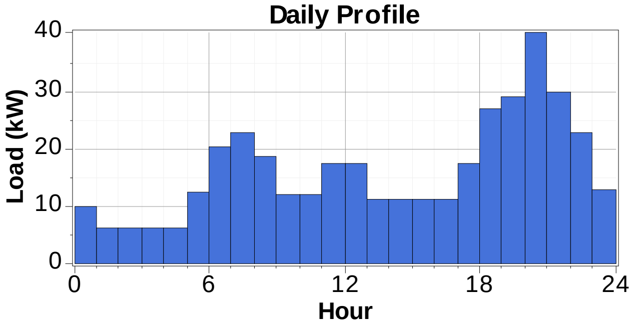

Fig. 4 Daily load profile

The hybrid power system can be powered by three power sources (wind, hydro and diesel). The wind turbine considered here is 20 kW squirrel cage induction generator (IG). The characteristic power curve of the wind turbine is presented in figure 5.

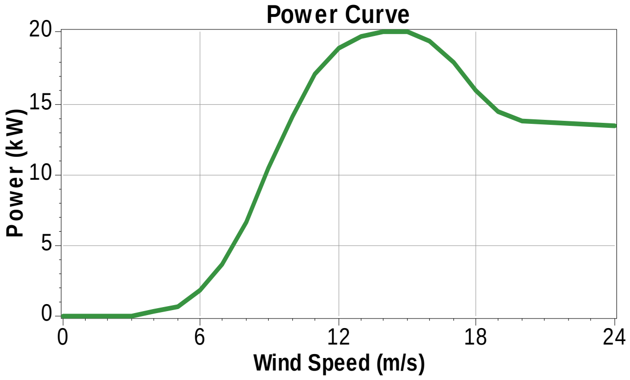

Fig. 5 Wind turbine power curve

The hydro and diesel generator are synchronous generators (SG) with a rated power of 16.6 kW and 10 kW. The input parameters for Homer optimization software are given in table 1.

Table 1 Hydro Turbine Data

Available head (m)	90
Design Flow rate (L/s)	25
Minimum flow ratio (%)	75
Maximum flow ratio (%)	150
Efficiency (%)	75

In order to increase the reliability of the system a battery storage system needs to be considered and a converter. The characteristics of the battery system is given in figure 6.

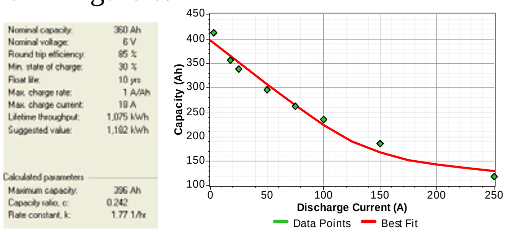

Fig. 6 Battery storage data

With all the input data given data and considering the system constraint the HOMER software will evaluate the optimal solution figure 7. The Optimal System Type graph figure 8 shows that if the average stream flow exceeds about 25l/s, the hydro system on its own is the least cost alternative.

	G20	Hydro (kW)	Dsl (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Dsl (hrs)
		16.6				$ 50,000	909	$ 59,701	0.255	1.00	0.00		
		16.6		4	2	$ 52,640	990	$ 63,209	0.270	1.00	0.00		
		16.6	10			$ 56,000	842	$ 64,989	0.278	1.00	0.00		0
		16.6	10	4	2	$ 58,640	923	$ 68,497	0.293	1.00	0.00		0
	1	16.6				$ 79,000	1,555	$ 95,597	0.409	1.00	0.00		
	1		10	24	4	$ 43,640	5,143	$ 98,541	0.422	0.65	0.00	5,040	2,240
	1	16.6		4	2	$ 81,640	1,636	$ 99,105	0.424	1.00	0.00		
			10	12	2	$ 10,320	8,383	$ 99,811	0.427	0.00	0.00	10,512	5,487
	1	16.6	10			$ 85,000	1,488	$ 100,885	0.432	1.00	0.00		0
	1	16.6	10	4	2	$ 87,640	1,569	$ 104,393	0.447	1.00	0.00		0
			10			$ 6,000	11,038	$ 123,832	0.530	0.00	0.00	14,391	8,760
	1		10			$ 35,000	9,325	$ 134,539	0.575	0.51	0.00	11,300	6,984

Fig. 7 HOMER optimization cases

If the stream flow is between 20 l/s and 25 l/s, HOMER suggests combining hydro with a diesel or a battery bank, or both. If the stream flow is less than 20 l/s, HOMER suggests either a diesel/battery system or, if the wind speed is high enough, a wind/diesel/battery system.

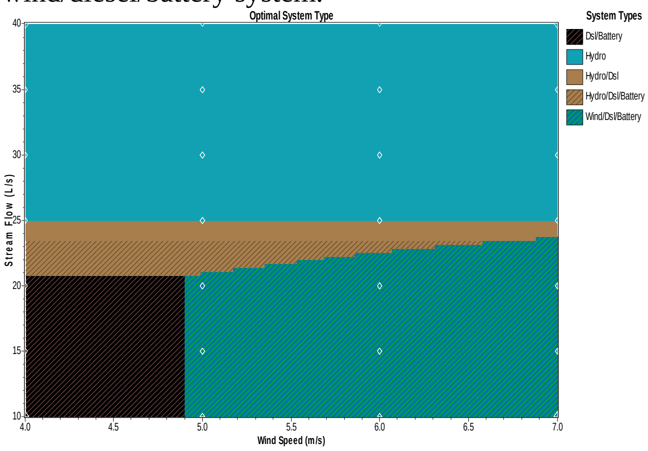

Fig. 8 HOMER Optimization Results chart

For the operational analysis we consider a optimal solution without battery storage consisting in two generators respectively one wind turbine and one hydro turbine. In order to evaluate the solution during normal operation mode we will build a simulation model based on the characteristics of the HOMER used generators.

4. Mathematical Model Of The Hybrid Asynchronous Machine Operating In Variable Speed Generator Mode

The optimal solution obtained from optimization is evaluated in the following paragraph . First we need to present wind-hydro mechanical and electrical models of the generators used .The modeling of the SG and IG is based on the equations (6) to (12).For the synchronous generator the d-q model is [13], [14]:

$$\dot{\omega}_s = \frac{1}{J_s}(-D_s\omega_s - T_s) \quad , \qquad (6)$$

$$\dot{\psi}_f = \frac{1}{\tau_{d0}}(-\psi_f + L_{nd} i_{sd}) + E_{fd} \quad , \qquad (5)$$

$$\begin{bmatrix} r_a & -\omega_s L_d & 1 & 0 \\ \omega_s L_q & r_a & 0 & 1 \\ r_1 & -\omega_s L_1 & -1 & 0 \\ \omega_s L_1 & r_1 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} i_{sq} \\ i_{sd} \\ V_{sq} \\ V_{sd} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} V_{bq} \\ V_{bd} \end{bmatrix} = \begin{bmatrix} \omega_s \frac{L_{md}}{L_f}\psi_f \\ 0 \\ 0 \\ 0 \end{bmatrix} , \qquad (7)$$

$$T_s = -\frac{L_{md}}{L_f}\psi_f i_{sq} - (L_d - L_q) i_{sq} i_{sd} \quad , \qquad (8)$$

where T_s is the air gap torque of SG, E_{fd}, ψ_f is the field voltage and field flux linkage of SG, J_s, D_s is the inertia and frictional damping factor, ψ_{rq}, ψ_{rd} is the rotor flux linkage components, r_s, r_a, L_s, L_r is the stator, rotor resistance and inductance V_{sq}, V_{sd} stator terminal voltage components of SG, i_{sq}, i_{sd} current component L_q, L_d, L_f, L_m q,d-axis, field, and mutual inductance ω_s bus frequency of SG.

The induction generator squirrel cage model is [15], [16]:

$$\dot{\psi}_{rq} = \frac{1}{\tau'_0}(-\psi_{rq} + L_m i_{aq}) + \omega_{base}(\omega_s - \omega_a)\psi_{rd} \quad , \qquad (9)$$

$$\dot{\psi}_{rd} = \frac{1}{\tau'_0}(-\psi_{rd} + L_m i_{ad}) - \omega_{base}(\omega_s - \omega_a)\psi_{rq} \quad , \qquad (10)$$

$$\begin{bmatrix} r_s & -\omega_s L'_s & 1 & 0 \\ \omega_s L'_s & r_s & 0 & 1 \\ r_2 & -\omega_s L_2 & (\omega_2^2 C_a L_2 - 1) & \omega_s r_2 C_a \\ \omega_s L_2 & r_2 & -\omega_s r_2 C_a & \left(\omega_2^2 C_a L_2 - 1\right) \end{bmatrix} \cdot \begin{bmatrix} i_{aq} \\ i_{ad} \\ V_{aq} \\ V_{ad} \end{bmatrix} +$$

$$+ \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} V_{bq} \\ V_{bd} \end{bmatrix} = \begin{bmatrix} \omega_s \frac{L_m}{L_r}\psi_{rd} \\ -\omega_s \frac{L_m}{L_r}\psi_{rq} \\ 0 \\ 0 \end{bmatrix} . \qquad (11)$$

The current balance of the systems is given in equations :

$$i_{sq} + i_{iq} - i_q - i_{ac.q} = 0, \; i_{sq} + i_{iq} - i_q - i_{ac.q} = 0 \quad , \qquad (12)$$

where C_a, ω_a are capacitor bank and angular speed of wind turbine, L_{md}, L_d d-axis field mutual inductance and transient inductance, i_{lq}, i_{ld} current component of the load, V_{cq}, V_{cd} AC side voltage of the converter of SG ω_l bus frequency of IG rotor, τ'_{d0}, τ'_0 transient open circuit time constant, T_a air gap torque of SG and IG; $i_{ac.q}, i_{ac.d}$ AC side current of the converter, r_1, r_2 L_1, L_2 resistance and reactance between SG and IG and bus; i_{iq}, i_{id} and IG into the bus $i_{aq}, i_{ad}, V_{aq}, V_{ad}$ stator terminal current and voltage of IG.

5 Matlab/Simulik Simulation Of The Hybrid Variable Speed Power System

The variable speed generator system presented in this case uses a 400 V, 10 kW synchronous machine, a wind turbine driving a 400 V, 20 kW induction generator, a 6 kW customer load and a variable secondary load (0 to 60 kW) (figure 9). At low wind speeds both the induction generator and the diesel-driven synchronous generator are required to feed the load.

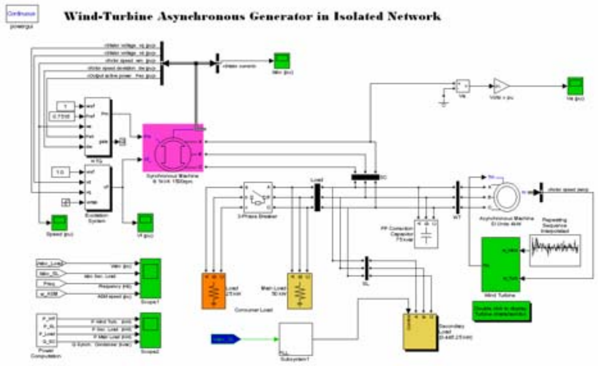

Fig. 9 Complete Hybrid variable speed System case 1 (no battery storage)

When the wind power exceeds the load demand, it is possible to shut down the hydro turbine. In this all-wind mode, the synchronous machine is used as a synchronous condenser and its excitation system controls the grid voltage at its nominal value. A secondary load bank is used to regulate the system frequency by absorbing the wind power exceeding consumer demand. The Secondary Load block (figure 10) consists of eight sets of three-phase resistors connected in series with GTO thyristor switches [17].

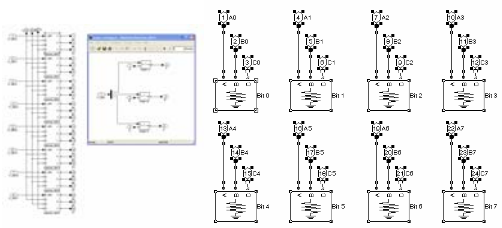

Fig. 10 Variable load regulator for the energy control in t he grid

The nominal power of each set follows a binary progression so that the load can be varied from 0 to

20kW by steps of 1 kW. GTOs are simulated by ideal switches.

The frequency of the grid is controlled by the Discrete Frequency Regulator block. This controller uses a standard three-phase Phase Locked Loop (PLL) system to measure the system frequency [18].

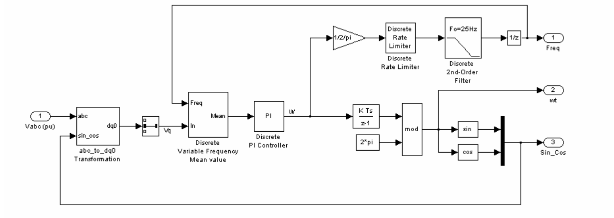

Fig. 11 PLL Filter structure

The measured frequency is compared to the reference frequency (60 Hz) to obtain the frequency error. This error is integrated to obtain the phase error. The phase error is then used by a Proportional-Differential (PD) figure 11 controller to produce an output signal representing the required secondary load power . This signal is converted to an 8-bit digital signal controlling switching of the eight three-phase secondary loads. In order to minimize voltage disturbances, switching is performed at zero crossing of voltage. the wind speed (10m/s) is such that the wind turbine produces enough power to supply the load.

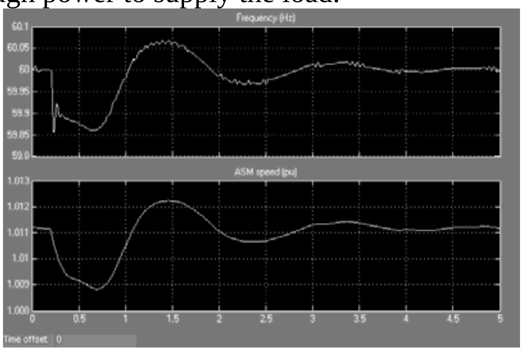

Fig. 12 Grid frequency variation

When the hydro turbine is stopped and then synchronous machine operates as a synchronous condenser with its mechanical power input (Pm) set at zero.

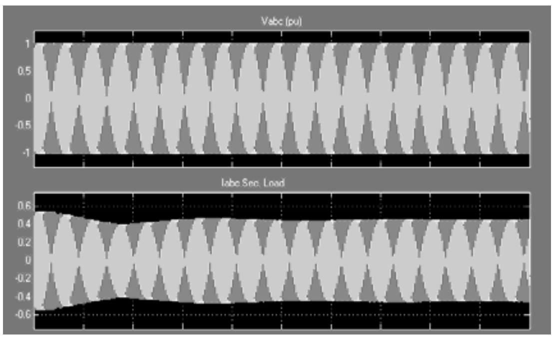

Fig. 13 Current and voltages

The frequency regulation system acts when an additional 1 kW customer load is switched on (figure 12). As the asynchronous machine operates in generator mode, its speed is slightly above the synchronous speed (1.011 pu).

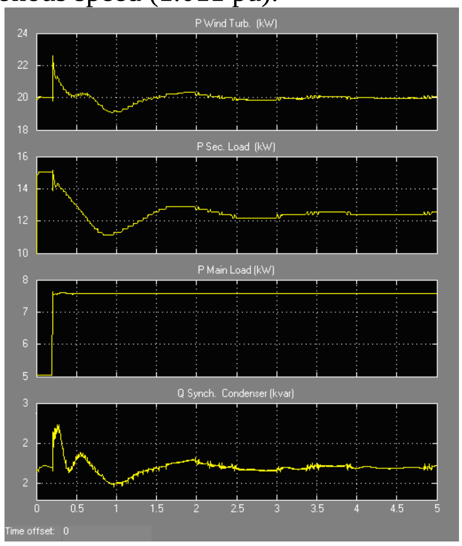

Fig. 14 Simulation results for system startup

According to turbine characteristics, for a 10 m/s wind speed, the turbine output power is 0.75 pu (14.070 kW). In this situation the wind turbine produces 20 kW. As the main load is 6 kW, the secondary load absorbs 15 kW to maintain a constant 50 Hz frequency. Voltage stays at 1 pu and no flicker is observed (figure 13).

At t=0.2 s, the additional load of 2 kW is switched on (figure 14). The frequency momentarily drops to 59.85 Hz and the frequency regulator reacts to reduce the power absorbed by the secondary load in order to bring the frequency back to 50 Hz.

4. Conclusions

The results from the simulation of renewable hybrid system shows that in it is important to look into the amount of excess energy the system produced. A reduction of 50% excess energy would have similar effect on the costs of energy. An alternative is to limit the load towards the dominant power supplier in the renewable energy hybrid system. This is to ensure that the initial capital and annualized cost to be at its minimum as it results from the HOMER optimization.

References:

[1] I., Boldea,Variable Speed Generators (Electric Power Engineering Series), CRC Press, 2005, ISBN 0849357152.

[2] T., Senjyu, T., Nakaji, K., Uezato, T., Funabashi, A., A Hybrid Power System Using Alternative Energy Facilities in Isolated Island, *IEEE Transaction on Energy Conversion*, vol. 20, no.2, June 2005, pp. 406-414.

[3] A., Yazdani, B., Iravani, A Neural-Point Clamped Converter System for Direct-Drive Variable-Speed Wind Power Unit, *IEEE Transaction on Energy Conversion*, vol. 21, no.2, June 2006, pp. 596-607.

[4] E., Muljadi, C. P., Butterfield, B., Parson, A., Ellis, Effect of Variable Speed Turbine Generator on Stability of a Weak Grid, *IEEE Transaction on Energy Conversion*, vol. 22, no.1, March 2007, pp. 27-36.

[5] F. D., Kanellos, N.D., Hatziargyriou, Control of Variable Speed Wind Turbines in Islanded Mode of Operation, *IEEE Transaction on Energy Conversion*, vol. 23, no.2, June 2008, pp. 535-543.

[6] F. S., Pai, S. J., Huang, Design and Operation of Power Converter for Microturbine Powered Distributed Generator with Capacity Expansion on Energy Conversion, *IEEE Transaction on Energy Conversion*, vol. 23, no.1, March 2008, pp. 110-118.

[7] B., Singh, G. K., Kasal, Voltage and Frequency Controller for a Three Phase Four-Wire Autonomous Wind Energy Conversion System, *IEEE Transaction on Energy Conversion*, vol. 23, no.2, June 2008, pp. 509-518.

[8] R., Fadaeinedjad, M., Moallem, G., Moschopoulos, Simulation of a Wind Turbine With Doubly Fed Induction Generator by Fast and Simulink, *IEEE Transaction on Energy Conversion*, vol. 23, no.2, June 2008, pp. 690-700.

[9] N. A., Schinas, N. A., Vovos, G. B., Giannakopoulos, An Autonomous System Supplied Only by a Ptch-Controlled Variable-Speed Wind Turbine, *IEEE Transaction on Energy Conversion*, vol. 22, no.2, June 2007, pp. 325-331.

[10] J. F. Ardanuy, J. R., Wilhelmi, J. J. F., Mora, J. I., Perez, Variable Speed Hydro Generation. Operational Aspects and Control, *IEEE Transaction on Energy Conversion*, vol. 21, no.2, June 2006, pp. 569-574.

[11] S. K., Kim, E. S., Kim, PSCAD/EMTDC – Based Modelling and Analysis of a Gearless Variable Speed Wind Turbine, *IEEE Transaction on Energy Conversion*, vol. 22, no.2, June 2007, pp. 421-430.

[12] M. Chinchilla, S., Arnaltes, J. C., Burgos, Control of Permanent-Magnet Generators Applied to Variable-Speed Wind-Energy Systems Connected to the Grid, *IEEE Transaction on Energy Conversion*, vol. 21, no.1, March 2006, pp. 130-135.

[13] B., Beltran, T., Ahmed-Ali, M. El H., Benbouzid, Sliding Mode Power Control of Variable-Speed Wind Energy Conversion System, *IEEE Transaction on Energy Conversion*, vol. 23, no.2, June 2008, pp. 551-558.

[14] D., Ramirez, C., Veganzones, F., Blázquez, Adaptation of Floating Paint DSP-Based Technology for Small Variable-Speed Wind Turbine, *IEEE Transaction on Energy Conversion*, vol. 22, no.2, June 2007, pp. 376-382.

[15] R., Pena, R., Cardenas, J., Proboste, J., Clare, G., Asher, Wind-Diesel Generating Using Doubly Fed Induction Machines, *IEEE Transaction on Energy Conversion*, vol. 23, no.1, March 2008, pp. 202-214.

[16] C., Abbey, G., Janos, Sizing and Power Management Strategies for Battery Storage Integration into Wind-Diesel Systems, Proceedings of the 34th International Conferences on Industrial Electronics, IECON 2008, Orlando, Florida, pp. 3376-3381.

[17] N., Milivojevic, I., Stamenkovic, N., Schofield, A., Emadi, Electrical Machines and Power Electronic Drives for Wind Turbine Applications, Proceedings of the 34th International Conferences on Industrial Electronics, IECON 2008, Orlando, Florida, pp. 2326-2331.

[18] T., Luu, A., Abedini, A., Nasiri, Power Smoothing of Doubly Fed Induction Generator Wind Turbines, Proceedings of the 34th International Conferences on Industrial Electronics, IECON 2008, Orlando, Florida, pp. 2365-2370.