Artículo de Investigación

Citación: Ramos-Paja, C., Saavedra-Montes, A. y Arango, E. (2012). Distributed maximum power point tracking in wind micro-grids. En: *Ingeniería, Vol. 17, No. 1, pág.* 5 - 13.

Distributed maximum power point tracking in wind micro-grids

Seguimiento distribuido del punto de máxima potencia en micro-redes eólicas

Carlos Andres Ramos-Paja
Universidad Nacional de Colombia
Facultad de Minas
caramosp@unal.edu.co

Andrés Julián Saavedra-Montes
Universidad Nacional de Colombia
Facultad de Minas
ajsaaved@unal.edu.co

Eliana Arango
Universidad Nacional de Colombia
Facultad de Minas
eiarangoz@unal.edu.co

Abstract

With the aim of reducing the hardware requirements in micro-grids based on wind generators, a distributed maximum power point tracking algorithm is proposed. Such a solution reduces the amount of current sensors and processing devices to maximize the power extracted from the micro-grid, reducing the application cost. The analysis of the optimal operating points of the wind generator was performed experimentally, which in addition provides realistic model parameters. Finally, the proposed solution was validated by means of detailed simulations performed in the power electronics software PSIM, contrasting the achieved performance with traditional solutions.

Key words: distributed operation, maximum power point tracking, wind generator.

Resumen

Con el objetivo de reducir los requerimientos de hardware en micro-redes basadas en aero-generadores, se propone un algoritmo para el seguimiento distribuido del punto de máxima potencia. Esta solución reduce la cantidad de sensores de corriente y unidades de procesamiento requeridas para extraer la máxima potencia en la micro-red en comparación con soluciones tradicionales, reduciendo el costo de la aplicación. El análisis de los puntos óptimos de operación de aero-generadores se realizó experimentalmente, lo que provee además parámetros realistas para los modelos de simulación. Finalmente, la solución propuesta se validó a través de simulaciones detalladas en el software PSIM, comparando el desempeño logrado contra soluciones tradicionales.

Palabras clave: Aero-generador, operación distribuida, seguimiento del punto de máxima potencia.

Fecha recibido: Mayo 17/2012
Fecha modificado: Junio 5/2012
Fecha aceptado: Junio 8/2012

1. Introduction

High wind energy penetration in the power system demands development in the operation and control of wind turbines to support its reliable function and the optimization of the power system efficiency. Figure 1 illustrates the structure of wind micro-grids composed by classical wind generation systems, where each generator is individually regulated to optimize its power production. Then, the power extracted from each generator is collected to be stored or injected into the grid. The power units depicted in Figure 1 are composed by power electronics devices, current sensors and controllers. Therefore, such micro-grids require as many current sensors and controllers as the number of wind generators.

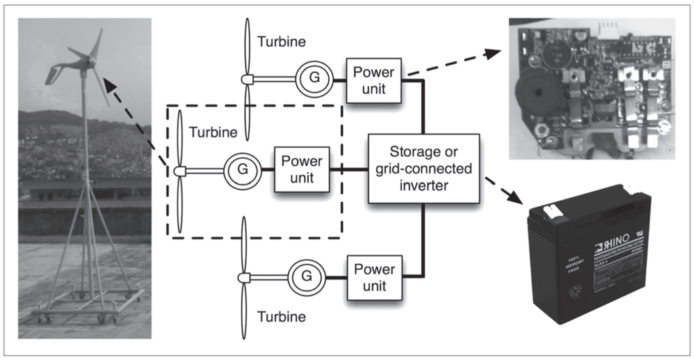


Figure 1. Wind micro-grid.

The power developed by wind generators depends on the wind speed, which has a variable nature. Additionally, wind generators characteristic has a maximum power point (MPP), which should be reached to improve the efficiency of the wind generator. Maximum power point tracking (MPPT) strategies have been developed and applied to extract the maximum power on wind generators. Therefore it is a common practice to apply an MPPT to each wind generator and this solution is called distributed MPPT (DMPPT). Although that solution optimizes the power extracted [1-3], its main requirement is a current sensor per wind generator system, which increases the hardware cost.

This paper is focused on a Multivariable Perturb and Observe (MVPO) strategy aimed at maximizing the power generated in wind micro-grids, reducing the requirements in terms of current sensors and control units. Such a solution increases the economical viability of wind power systems, since the same power is extracted in comparison with classical wind micro-grids, but a reduced number of components are required. This is an extended version of preliminary results appearing in the 2012 IEEE Workshop on Engineering Applications [4]. The paper is organized as follow: In Section 2 the wind generation system is described and modeled; additionally the maximum power point of this system is put in evidence through the power and current voltage curves. In Section 3, the MVPO algorithm proposed in this work is described and compared with a MPPT based on Perturb and Observe (P&O) algorithm. Simulations results that confirm the maximum power extraction using the proposed algorithm are presented in Section 4, and finally, conclusions are given in Section 5.

2. Wind generator maximum power point

Some wind generation systems use permanent magnet synchronous generators (PMSG) [5] that do not require excitation control systems. In such wind generators, there is common to adopt a passive rectifier and a dc/dc converter to perform the tracking of the optimal operating point or MPP as depicted in Figure 2. The MPP is characterized by producing the maximum output power Pmpp for a given rotor angular speed n, which is defined by the wind condition and turbine characteristics.

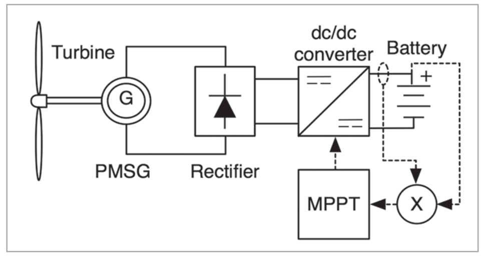


Figure 2. Wind generation system.

Figure 2 considers the dc/dc converter interacting with a dc system, which could be a battery bank or a dc-link regulated by a grid-connected inverter [5]. The main objective of the dc/dc converter is to regulate the generator current to maximize the power delivered to the battery terminals. The optimal operating point is tracked by the MPPT following the current perturbation that guarantees a positive power change. Finally, such an optimal operating point is defined by means of the generator voltage Vmpp and current Impp, as the following relation holds: Pmpp = Impp • Vmpp.

2.1. Wind turbine and generator models

In this section the wind turbine model and the permanent magnet synchronous generator model [6] are presented. These models are implemented to simulate a wind micro-grid and validate the MPPT strategy proposed in this work. Wind turbine power P_{tur} is calculated from Equation (1):

$$P_{tur} = 0.5 A_{tur}\, \rho\, v_{wind}^{3} C_P \tag{1}$$

where the swept area of the turbine rotor is A_{tur} in m^2, the air density in the turbine location is ρ in Kg/m^3, the wind speed is v_{wind} in m/s, and C_P is the power coefficient, which is function of the Tip Speed Ratio (λ) that represents the ratio between the tip and the wind speed. λ is defined in Equation (2), where the turbine speed is represented by ω_{tur} in rad/s:

$$\lambda = \frac{\omega_{tur} R}{v_{wind}} \tag{2}$$

The wind turbine model simulated in this work adopts a coefficient power presented in Equation (3):

$$C_P = c1\left(c2 - c3\beta - c4\beta^{x} - c5\right)e^{-c6} + c7\,, \tag{3}$$

with coefficients: $c1 = 0.5$, $c2 = 116\lambda'$, $c3 = 0.4$, $c4 = 0$, $c5 = 5$, $c6 = 21\lambda'$, $c7 = 0.01\lambda$, β is the blade pitch angle, and λ' is given by Equation (4).

$$\lambda' = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

Finally the equation of motion of the turbine and the generator is given by Equation (5):

$$T_{tur}(t) - T_{elec}(t) = J\frac{d\omega_{tur}}{dt} + B\,\omega_{tur}\,, \tag{5}$$

where the mechanical torque of the turbine is T_{tur}, and the electromagnetic torque of the generator is T_{elec}. Both torques are given in N • m. The moment of inertia of the wind turbine and the PMSG is J in kg • m^2, and the damping coefficient is B, which is considered equal to 0 since the friction is negligible in comparison with the rotor inertia effect.

A three phase permanent magnet synchronous generator is represented by Equation (6):

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R_S & 0 & 0 \\ 0 & R_S & 0 \\ 0 & 0 & R_S \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix} \tag{6}$$

where the stator phase voltage, currents, and flux linkages are v_a, v_b, v_c, i_a, i_b, i_c, ϕ_a, ϕ_b, and ϕ_c respectively. In the rotational reference frame dq, Equation (6), can be expressed by Equations (7) and (8):

$$v_d = R_S i_d(t) + L_S \frac{di_d(t)}{dt} - e_q(t) \tag{7}$$

$$v_q = R_S i_q(t) + L_S \frac{di_q(t)}{dt} + e_d(t) \text{ ,} \tag{8}$$

where the dq stator voltage and currents components are v_d, v_q, i_d, and i_q respectively. The stator winding resistance and inductance are represented by R_S and L_S. The electromotive force dq components are e_d and e_q, which are determined by Equations (9) and (10). In there, the electric rotor speed is denoted as ω_e.

$$e_d(t) = \omega_e(t)\,(L_S i_d(t) + \varphi_r) \tag{9}$$

$$e_q(t) = \omega_e(t)\, L_S i_q(t) \tag{10}$$

These electromotive forces represent the addition of the electromotive forces induced by the dq flux linkage components of the stator and the electromotive force induced by the flux linkages of the permanent magnets of the rotor (ϕ_r) in a PMSG. The PMSG and the wind turbine models in addition with the rectifier and dc/dc converter models are simulated to evaluate the MPPT algorithm proposed in the PSIM power electronics simulator.

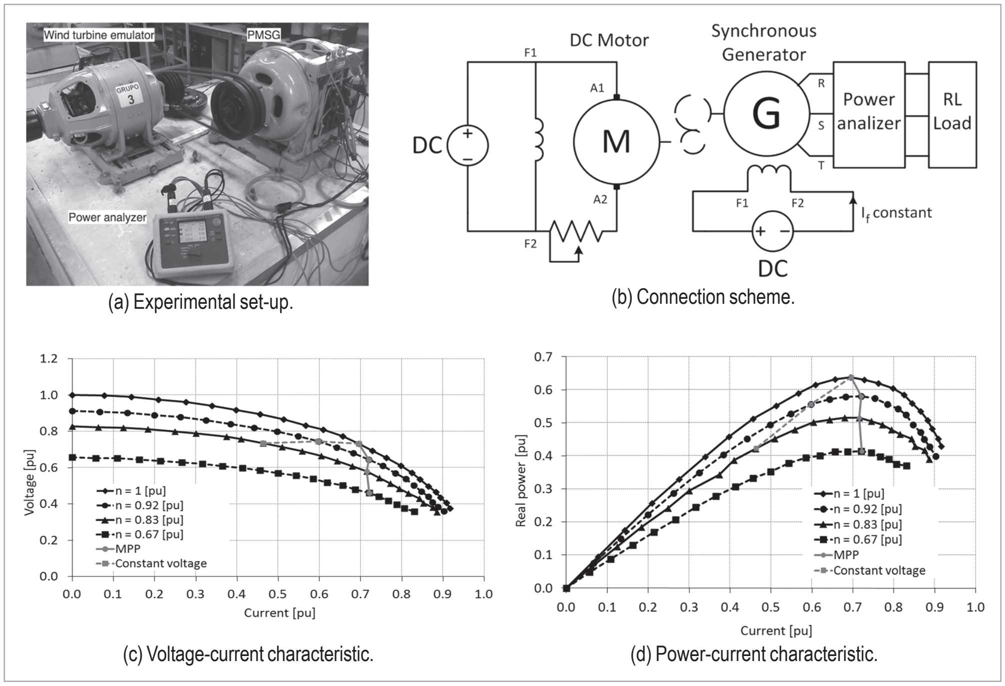
2.2. Maximum power points

From the previous model it is noted that the generator voltage changes for the rotor angular speed defined by the turbine model and the wind profile, and also changes for the requested current defined by the dc/dc converter.

To experimentally validate such analyses, a PSGM was configured by keeping the field current constant in a synchronous generator. Besides, the rotor angular speed was set by a DC motor. Figure 3(a) shows the experimental set-up and Figure 3(b) depicts the connection scheme. Figure 3(c) and 3(d) show the generator voltage-current and power-current characteristics for different angular speed. The figures also depict the position of the MPP, which changes for all the wind speed conditions, and the constant voltage operating points. The MPP position, given by its current Impp and voltage Vmpp, depends on the balance among the power increment generated by changes on the generator current, and the increment of the losses generated by such a current step-up. Therefore, the MPP position is difficult to predict in normal operating conditions when the wind speed is not constant.

Moreover, such results put in evidence that the generator current must be set to Impp depending on the wind speed condition, which in addition can change at any moment. Such a procedure is performed by means of the dc/dc converter, which can be regulated in current mode to ensure the extraction of a given generator current.

Figures 3(c) and 3(d) also reveal the non-linearity of the required voltage-current profile that must be imposed by the dc/dc converter to the generator, which implies that the operating conditions must be optimized online. In conclusion, for a non-constant wind profile, which is the most common condition, the dc/dc converter input current must change; but to ensure an optimal operation, the current imposed must follow the MPP trace of Figure 3(c). Finally, the procedure of tracking the optimal operation condition is commonly named Maximum Power Point Tracking or MPPT, and different optimization algorithms are adopted for such aim.



(a) Experimental set-up. (b) Connection scheme.

(c) Voltage-current characteristic. (d) Power-current characteristic.

Figure 3. PMSG experimental system and static characteristics.

3. Maximum power point tracking algorithm

The Perturb and Observe (P&O) algorithm is widely adopted for optimizing the operating point of photovoltaic generation systems [7, 8], and also it has been used in recent works to optimize wind generation systems [3, 9].

Figure 4 shows the flowchart of the P&O algorithm, where the generator current imposed by the dc/dc converter, is modified to track the MPP: the current is perturbed in one direction (increased or decreased), and depending of the power extracted from the generator, the current is perturbed again. For example, referring to Figure 3(d), assuming that the wind turbine imposes a n = 1 pu to the generator, and considering a generator current Ig = 0.6 pu, the P&O

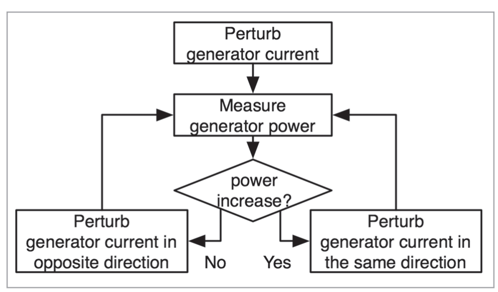


Figure 4. Perturb and observe algorithm.

algorithm perturbs Ig in ΔIg value, obtaining Ig = 0.6 pu + ΔIg. In such a case, the generator power is increased, therefore Ig is perturbed again in the same direction. Such a procedure continues up to Ig = 0.7 pu where the generator reaches an operating point near to MPP. Then, Ig is increased again where the generator power is decreased in comparison with Ig = 0.7 pu, so the next perturbation will decrease Ig. From such a condition, the generator current will oscillate around the MPP with amplitude equal to ΔIg.If the wind speed changes, so the rotor angular speed also, the P&O controller tracks the new MPP to oscillate around it. Such an optimization algorithm changes the perturbation sign that guarantees a positive change on the power.

It is noted that the P&O algorithm requires measuring the generator power; therefore the converter output current must be sensed. Such a procedure increases the solution cost since efficient current sensors are costly devices, while if cheap resistive current sensors are adopted, they introduce power losses degrading the system efficiency.

In wind micro-grids composed by multiple generation systems as in Figure 1, the classical solution considers the simultaneous operation of the complete power systems composed by the generator, the power stage, the current sensor and the P&O controller as in Figure 2. Therefore, the number of processing units and current sensors are in agreement with the number of generators. But taking into account that the collected power will be stored or injected into the grid, the optimization of each wind generator operation is equivalent to optimize the operating point of the whole micro-grid.

To maximize the wind micro-grid output power, an extension of the P&O algorithm is adopted to optimize all generator currents. Such a multivariable P&O algorithm, named MVPO, is designed to optimize each generator operating point by using the P&O principle: the current of the first generator is perturbed meanwhile the aggregated output power increases, then, when the power is decreased, the current of the second generator is perturbed in the opposite direction with respect to the last perturbation performed to that generator. The procedure is iteratively performed to cover all the generators available in the micro-grid. Figure 5 illustrates the MVPO algorithm by means of a two-generator MVPO flowchart: if the power is increased, the current of the last perturbed generator is perturbed again in the same direction previously adopted. Otherwise, if the power is decreased, the last generator current is blocked, and the other generator current is perturbed in the opposite direction, performing a P&O like procedure. The MVPO algorithm changes the perturbation sign of both generator currents that guarantee a positive change on the power, i.e. a positive power gradient.

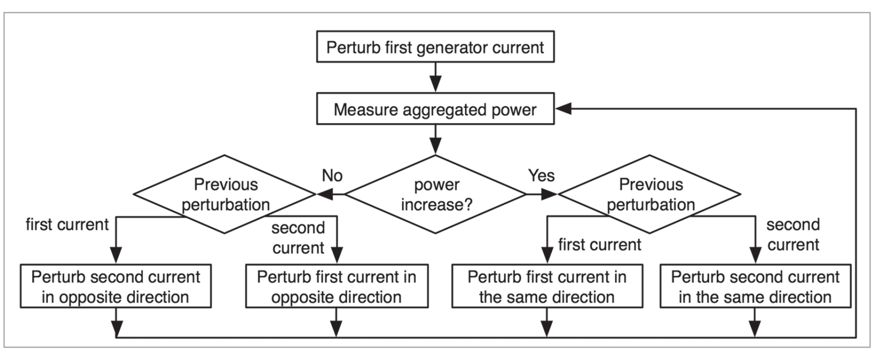


Figure 5. Multivariable Perturb and Observe algorithm.

It is noted that the MVPO requires the acquisition of the aggregated wind micro-grid power only, instead of each generator power, which implies a reduction of N-1 current sensors with respect to the classical solution, where N represents the number of generators. Moreover, the MVPO generates the N current commands that must be imposed by the dc/dc converters to the micro-grid generators to maximize the whole power production. In addition, since the MVPO optimizes the operating point of all the generators, a single control unit is required instead of N as in the classical solution.

Finally, the MVPO improves the implementation of wind micro-grid by significantly reducing the number of current sensors and control units required.

4. Implementation and simulation results

To illustrate the performance of the MVPO solution, a two-generator micro-grid was simulated considering the models of Section 2.1 and the parameters of the experimental system presented in Section 2.2, for both P&O and MVPO approaches. Figure 6 presents the simulation scheme, where boost dc/dc converters were adopted since they introduce low current ripple to the generator, and allow to step-up the voltage to the storage or grid-connected inverters requirements, which makes the boost topology one of the most commonly used in wind power systems [5, 10, 11].

Figure 6 also considers the current regulation of the boost dc/dc converters by means of the sliding-mode control (SMC) technique [12], which is widely used for current-mode dc/dc converters [13]. Such a non-linear technique provides a fast tracking of the reference with the fastest response allowed by the dc/dc converter, and its design was performed as reported in [12, 13]. Therefore, the dc/dc converters can be considered as the actuators of the P&O and MVPO control algorithms.

Considering the classical P&O algorithm, each generator operation is optimized by a dedicated P&O controller, requiring also a current sensor for each one. In this way, the implementation of the classical solution uses two current sensors to obtain I_{o1} and I_{o2} in Figure 6. Instead, the MVPO requires to calculate only the output power of the whole micro-grid, therefore simply the aggregated output current must be measured requiring just a single current sensor. This can be observed in the implementation of Figure 6, where only the aggregated current I_{oa} is measured to calculate the micro-grid output power P_{oa} used by the single MVPO to generate the current references for all the SMC of the dc/dc converters. This aspect implies that the MVPO solution significantly improves the implementation of multi-generators installations.

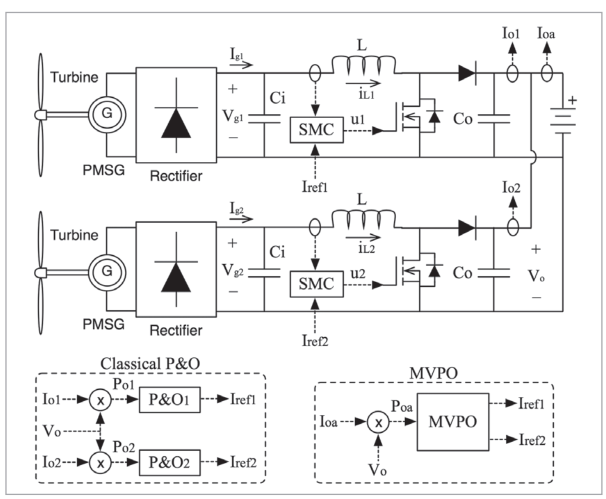
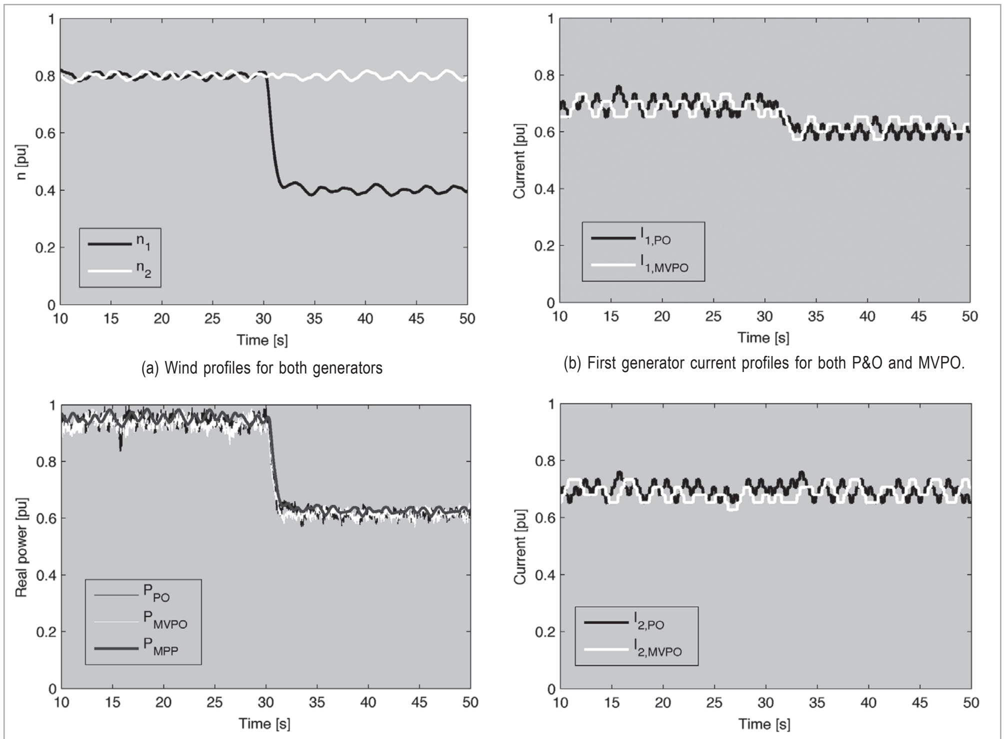


Figure 6. Two-generator micro-grid to test both P&O and MVPO algorithms.



(a) Wind profiles for both generators

(b) First generator current profiles for both P&O and MVPO.

(c) Aggregate power generated by both P&O and MVPO.

(d) Second generator current profiles for both P&O and MVPO.

Figure 7. Dynamic simulation.

Figure 7 presents the simulation results considering both P&O and MVPO approaches: Figure 7(a) shows the angular speed imposed by the wind profiles and turbine model to the generators, where the noise in the profiles is a consequence of the generator and turbine inertias interaction. The angular speed begins at 0.8 pu, and 30 s later the speed of the first generator is reduced to 0.4pu. Figures 7(b) and 7(d) show the current references imposed to the SMC of the dc/dc converters by both the P&O and MVPO controllers. In such figures it is noted that both controllers impose the same average current to the generators, therefore both P&O and MVPO define the same operating points. Figure 7(c) verifies such a condition since the output power of the micro-grid for both approaches is the same. Moreover, Figure 7(c) also presents the maximum power available for the given wind profiles (P_{MPP} trace). Therefore, both P&O and MVPO solutions accurately track the MPP for multiple generators.

5. Conclusion

The position of the maximum power points in wind generators was experimentally analyzed to propose a tracking algorithm. Such an algorithm was designed to reduce the hardware required to implement wind micro-grids, saving N-1 current and voltage sensors, and N-1 processing units, where N represents the number of wind generation systems. The proposed solution is based on a distributed MPPT algorithm, which exhibits the same efficiency in the tracking of the MPP in comparison with classical solutions. As a consequence the MVPO reduces implementation costs.

We remark that this solution can be extended to support micro-grid consisting of different power sources such as photovoltaic generators, fuel cells and wind generators. Finally, voltage-based control techniques can be designed to track the generator MPP avoiding the requirement of high-frequency currents sensors, which are necessary in current-based controllers.

Acknowledgment: This work was supported by scholarship 095-2005 from COLCIENCIAS, GAUNAL group from Universidad Nacional de Colombia, and GIT group from Instituto Tecnológico Metropolitano under the projects MECOVA-WIND and VECTORIAL-MPPT.

References

[1] M. Kesraoui, N. Korichi, and A. Belkadi, "Maximum power point tracker of wind energy conversion system," *Renewable Energy,* vol. 36, pp. 2655-2662.

[2] M. Abdel-Salam, A. Ahmed, and M. Abdel-Sater, "Maximum power point tracking for variable speed grid connected small wind turbine," in *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International*, pp. 600-605.

[3] V. Agarwal, R. K. Aggarwal, P. Patidar, and C. Patki, "A Novel Scheme for Rapid Tracking of Maximum Power Point in Wind Energy Generation Systems," *Energy Conversion, IEEE Transactions on,* vol. 25, pp. 228-236, 2010.

[4] C. A. Ramos-Paja, A. J. Saavedra-Montes, and E. Arango, "Maximum power point tracking in wind farms by means of a multivariable algorithm," in *2012 Workshop on Engineering Applications (WEA)*, 2012, pp. 1-6.

[5] J. A. Baroudi, V. Dinavahi, and A. M. Knight, "A review of power converter topologies for wind generators," *Renewable Energy,* vol. 32, pp. 2369-2385, 2007.

[6] T. Ackermann, *Wind Power in Power Systems*, First ed.: Wiley, 2005.

[7] A. I. Bratcu, I. Munteanu, S. Bacha, D. Picault, and B. Raison, "Cascaded DC-DC Converter Photovoltaic Systems: Power Optimization Issues," *Industrial Electronics, IEEE Transactions on,* vol. 58, pp. 403-411, 2011.

[8] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, "A Technique for Improving P&O MPPT Performances of Double-Stage Grid-Connected Photovoltaic Systems," *Industrial Electronics, IEEE Transactions on,* vol. 56, pp. 4473-4482, 2009.

[9] J. C. U. Peña, M. A. G. de Brito, G. de A. e Melo, and C. A. Canesin, "A comparative study of MPPT strategies and a novel singlephase integrated buck-boost inverter for small wind energy conversion systems," in *Power Electronics Conference (COBEP), 2011 Brazilian*, pp. 458-465.

[10] M. Arifujjaman, "Modeling, simulation and control of grid connected Permanent Magnet Generator (PMG)-based small wind energy conversion system," in *Electric Power and Energy Conference (EPEC), 2010 IEEE*, pp. 1-6.

[11] R. Morales, R. Ordoez, M. A. Morales, and V. Flores, "Control System Design and Simulation of an AC/DC - DC/DC - DC/AC Power Converter for a Permanent Magnet Wind Power Generator in Rural Power Generation," in *Electrical, Communications, and Computers, 2009. CONIELECOMP 2009. International Conference on*, 2009, pp. 79-83.

[12] C. A. Ramos-Paja, A. J. Saavedra-Montes, R. Giral, J. D. V. Hincapié, and R. A. R. Angel, "Design, modeling, control and implementation of a fuel cell generation system," *Revista Facultad de Ingenieria,* vol. 59, pp. 9-22, 2011.

[13] E. Bianconi, J. Calvente, R. Giral, G. Petrone, C. A. Ramos-Paja, G. Spagnuolo, and M. Vitelli, "A fast current-based MPPT technique based on sliding mode control," in *Industrial Electronics (ISIE), 2011 IEEE International Symposium on*, 2011, pp. 59-64.

Carlos Andrés Ramos-Paja
Ingeniero Electrónico de la Universidad del Valle, Colombia. Obtuvo su título de Maestría en Automática en la Universidad Valle, Colombia; y su título de Maestría en Ingeniería Electrónica de la Universitat Rovira i Virgili de Tarragona, España. Obtuvo su Doctorado en la Universitat Rovira i Virgili de Tarragona, España. Actualmente se desempeña como profesor en el área de Desarrollo Tecnológico e Industrial en la Universidad Nacional de Colombia, Medellín, Colombia, y pertenece como investigador al grupo de investigación GAUNAL donde realiza estudios sobre electrónica de potencia, fuentes alternas de energía y control de generadores sincrónicos.

Andrés Julián Saavedra-Montes
Ingeniero Electricista de la Universidad del Valle, Colombia. Obtuvo su título de Maestría en Sistemas de generación de energía eléctricay su título de Doctorado en Ingeniería en la Universidad del Valle, Colombia. Actualmente se desempeña como profesor en el área de Desarrollo Tecnológico e Industrial en la Universidad Nacional de Colombia, Medellín, Colombia, y pertenece como investigador al grupo de investigación GAUNAL donde realiza estudios sobre electrónica de potencia, fuentes alternas de energía y control de generadores sincrónicos.

Eliana Isabel Arango Zuluaga
Ingeniera Electrónica de la Universidad de Antioquia, Colombia. Obtuvo su Diploma de Estudios Avanzados DEA y su título de Doctorado en la Universitat Rovira i Virgili de Tarragona, España. Actualmente se desempeña como profesora en el área de Desarrollo Tecnológico e Industrial en la Universidad Nacional de Colombia, Medellín, Colombia, y pertenece como investigadora al grupo de investigación GAUNAL donde realiza estudios sobre electrónica de potencia y fuentes alternas de energía.