A PEAK POWER TRACKER FOR SMALL WIND TURBINES IN BATTERY CHARGING APPLICATIONS

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Abstract: This paper describes the design, implementation and testing of a prototype version of a peak power tracking system for small wind turbines in battery charging applications.

The causes for the poor performance of small wind turbines in battery charging applications are explained and previously proposed configurations to increase the power output of the wind turbines are discussed.

Through computer modeling of the steady-state operation the potential performance gain of the proposed system in comparison with existing systems is calculated. It is shown that one configuration consisting of reactive compensation by capacitors and a DC/DC converter is able to optimally load the wind turbine and thus obtain maximum energy capture over the whole range of wind speeds.

A proof of concept of the peak power tracking system is provided by building and testing a prototype version The peak power tracking system is tested in combination with a typical small wind turbine generator on a dynamometer. Steady-state operating curves confirming the performance improvement predicted by calculations are presented.

Keywords: wind turbine, battery charging, DC/DC converter

I. INTRODUCTION

The designers of small turbines (up to about 40kW) stress simplicity over complexity and the machines are designed for little or no maintenance. Most use direct-drive permanent-magnet synchronous alternators and are passively directed into the wind by a tail vane. Integrated horizontal-axis upwind-rotor designs, simplified to reduce the number of moving parts have emerged as the most successful general configuration.

PE-386-EC-0-01-1999 A paper recommended and approved by the IEEE Energy Development and Power Generation Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Energy Conversion. Manuscript submitted July 10, 1998; made available for printing January 28, 1999.

* currently with the Netherlands Energy Research Foundation.

By far the most important application of small wind turbines are the so-called stand-alone systems that provide electricity in places that do not have access to a power grid. In industrialized countries such applications are mainly rural (electrification of fences, water pumping) and to a lesser extent residential (remote houses not connected to the utility grid). The dominant share of the market for small wind turbines however lies in the developing world. Hybrid systems powering mini-grids in remote villages often incorporate wind turbines, with or without photo-voltaic (PV) or other renewable components. The variability and intermittent character of renewable resources requires the system to have back-up generation capability and/or energy storage, the latter usually a battery bank. A nominal battery bank voltage of 120 or 240V is common. In battery charging stations, batteries are connected in series and in parallel and the whole battery bank is charged through a wind turbine or PV panels. Batteries are delivered weekly to the homes of the individual users.

Field experience has shown that both the peak power output and the total energy capture of small variable-speed wind turbines in battery charging applications often fall short of expectations based on rotor size and generator rating.

II. THEORETICAL BACKGROUND

The conversion efficiency of the system from wind power to electrical power is given by the product of the power coefficient C_p, the gearbox (if present) efficiency, alternator efficiency and power-electronic converter efficiency. C_p is limited to a maximum of 0.59 (Betz limit). Overall efficiency is defined as the average conversion from energy available in the wind to electrical energy produced.

The mechanical power developed by a wind turbine rotor varies according to the equation

$$P_m = \frac{1}{2} C_p \rho \pi R^2 v_w^3 \qquad (1)$$

where C_p=power coefficient, ρ=air density, R=radius of blades, and v_w=wind speed. The power coefficient is the ratio of the mechanical power at the turbine shaft to the power available in the wind. A variety of aerodynamic factors affect this power coefficient including blade design parameters such as number of blades, airfoil sections, surface finish and angle of attack (orientation of the blade in the airflow). The power coefficient is usually given as a function of tip-speed-ratio λ :

$$\lambda = \frac{\text{tip speed of rotor blades}}{\text{wind speed}} = \frac{\Omega\,R}{v_W} \quad (2)$$

where Ω = angular velocity. Hence for a given wind speed the available rotor power can be plotted versus the alternator frequency, this is done in Fig. 1 for v_w=4,6,8,10 m/s for a typical 7m diameter rotor coupled to a 38 pole direct-drive alternator. In order to extract peak power, the rotor must be held at its optimal tip speed ratio, which means that the rotor angular velocity must vary proportionally to wind speed. Since rotor angular velocity is proportional to alternator frequency, at optimal tip speed ratio the maximum available rotor power also varies as the cube of the alternator frequency, as shown in Fig. 1 for the same rotor-generator combination.

Whether used in a battery charging station or in a hybrid village power system, the AC power of small wind turbines is usually rectified and fed into a battery bank. In existing systems this is done by simple diode rectification and direct connection to the fixed-voltage DC bus of the system. In [1] the power transferred from the generator to the battery bank as a function of generator frequency is calculated using an equivalent circuit.

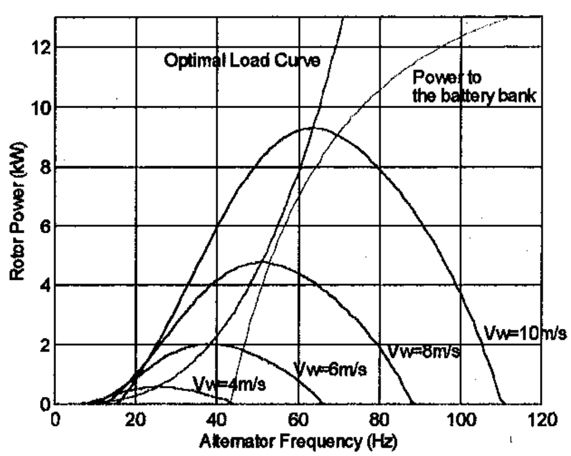

Fig. 1 Wind turbine maximum available rotor power (optimal load curve) and generator power curve with fixed bus voltage (power to the battery bank)

Fig. 1 shows the mechanical (shaft) power vs. frequency calculated for 12kW multiple-pole generator connected through a diode rectifier to a battery bank with a nominal voltage of 240V. Note that there is a limiting alternator speed (cut-in speed) dependent upon the battery bank voltage, below which the generator terminal voltage is less than the battery voltage. Obviously, below this cut-in point the alternator produces no power output. From cut-in speed through the rated shaft speed of the generator the output power increases with frequency.

The torque capability is limited by the characteristic of the synchronous generator. For a constant terminal voltage, the only way to change the torque is to adjust the rpm of the generator. Thus in the system with the fixed DC bus voltage, the characteristic of the power generation is dependent upon the wind turbine (rotor speed) and the generator (flux and synchronous impedance). As the rotor speed (proportional to generator frequency) increases, there will be a corresponding stator current, power, torque and power angle. In Fig. 1 it can be seen that above a certain rotor speed the output power becomes virtually constant and the system output power is naturally limited.

In Fig. 1 the curves for maximum rotor power (optimal load line) and alternator electrical power for a system with a nominal battery bank voltage of 240V are superimposed in order to illustrate that the effective system output is limited by the lower curve. At low wind speeds the available rotor power is lost because the alternator voltage is below the battery bank voltage. At high alternator speeds the available rotor power well exceeds the alternator output and again there is a substantial loss in energy capture. This mismatch of rotor and alternator characteristic leads to operation of the turbine away from the optimum load line (the turbine is not operating at maximum power coefficient) with a resultant reduction in output. It is clear that in existing systems the power going into the battery bank is limited by the electrical characteristics. An optimal battery bank voltage can be selected to obtain a maximum power output at a certain alternator frequency. However, the choice of an optimal battery bank voltage according to the site's average wind speed is always a trade-off: the gain in power output at high wind speeds is partly compensated by a loss in power output at low wind speeds (or vice versa).

The problem of low overall efficiency of wind turbines in battery charging applications has been identified and investigated before. In [2],[3],[4],[5] and [6] solutions have been proposed to match the generator output power curve with the wind power curve and subsequently increase the overall efficiency of small wind turbine systems in battery charging applications. However none of the previously investigated approaches give a satisfying solution. Several can only increase the system's power output in the lower wind speed range and require rewinding of the alternator in order to achieve increased power output over the whole wind speed range. Others impose strict limitations on the system's battery bank configuration prohibiting an optimal DC bus voltage. So far no results at power levels of several kilowatts have been presented.

It is clear that by changing the characteristics of the load applied to the generator the wind turbine power generation can be optimized. In contrast to a system with an uncontrolled rectifier, where the turbine rotor accelerates or decelerates as necessary to balance the rotor output power and the generator input power, the turbine speed is controlled by adjusting the output power of the wind turbine alternator. The load on the generator is controlled by controlling the voltage at the terminals of the generator. By inserting a DC/DC converter between the rectifier output and the DC battery, the apparent DC bus voltage seen by the generator can be changed effectively controlling the generator terminal voltage. The converter varies the voltage on its input side (which is the rectifier output voltage) so as to cause maximum power transfer from the generator to the battery bank. Another method of increasing the electric power transfer from the generator to the battery is to insert series capacitors between the terminals of the generator and the input to the rectifier. The capacitors are sized such that at higher operating frequencies, the capacitive reactance tends to cancel the inductive reactance of the generator stator, lowering the generator's effective impedance.

In the investigated configuration both approaches have been combined. The electrical circuit is shown in Fig. 2. This system simultaneously achieves the voltage-optimizing benefits of the DC/DC converter with the generator impedance-reducing benefits of the series capacitors, resulting in a greater performance improvement than is attainable with either feature alone. The combination of the series AC capacitance, rectifier, and the DC/DC converter and its control circuit is referred to as Peak Power Tracker (PPT).

The converter is capable of increasing or decreasing the input voltage. Hence increased energy capture will be possible both at the high and the low end of the wind speed range. By including a PPT in a small wind turbine system feeding into a DC bus or a battery bank, the effective output power of the system is no longer limited by the electrical components.

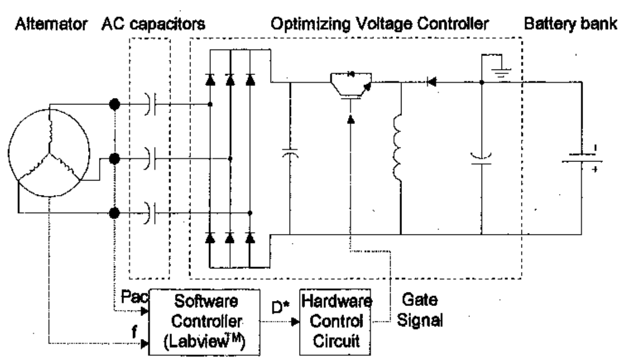

Fig. 2 Components of the Peak Power Tracker

The generator maximum power curve of the proposed configuration and the maximum rotor power curve are shown in Fig. 3. The curves are calculated based on an equivalent circuit that takes into account the voltage control of the converter and the series reactance of the capacitors.

Wherever the generator maximum power curve lies above the maximum rotor power curve, the generator is able to capture all the available power from the wind. Figure 3 shows how the generator is now able to closely track the optimal rotor power curve over a wide range of wind speed in comparison with the power curve of a wind turbine generator with a fixed DC bus voltage. At a certain wind speed, the output power can be limited in order not to exceed the alternator current limit.

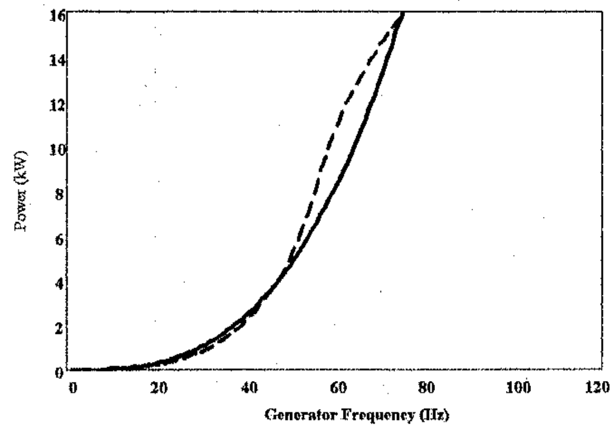

Fig. 3 Modeling results : Maximum rotor power curve (solid), maximum generator power curves for system with Peak Power Tracker (dotted)

III. Design and construction of a Peak Power Tracker prototype

A Peak Power Tracker was built to be tested in combination with a variable-speed wind turbine and a battery bank. The wind turbine has a rated (electrical) power of 12kW, the battery bank its nominal voltage was 240V. The Peak Power Tracking system is placed in between the wind turbine alternator and the battery bank. It consists of AC series capacitors, a diode-bridge rectifier, and a DC/DC converter and its controller.

The optimal value of the AC series capacitance is determined based on calculations of the steady state operating mode. A reactive compensation of 400mF per phase enables the generator to operate on the target power curve over a wide frequency range. The AC voltage is rectified through an uncontrolled diode bridge rectifier.

The function of the converter is to vary the DC voltage on its input side according to a signal provided by a controller. The controller/converter combination is referred to as the Optimizing Voltage Controller (OVC). Because the OVC is regulating the rectifier output voltage, it is effectively controlling the AC voltage at the rectifier input. The generator terminal voltage is dependent on the generator frequency and the load and hence changes with the wind speed. To match the generator output voltage with the battery bank voltage in all operating conditions, the converter will have to step up the generator voltage at low wind speeds and reduce the generator voltage at high wind speeds. Given these requirements, the chosen topology is a buck-boost converter.

An important issue in the design of the converter is the presence of parasitic elements. Parasitic elements have a significant impact on the voltage conversion ratio and the stability of the buck-boost converter. At high values of the duty cycle, parasitic elements limit the voltage conversion ratio and very poor switch utilization makes operation at high duty cycles impractical [7]. In this application the input voltage range is very wide and consequently a wide range of voltage conversion ratio is required. Minimizing the influence of parasitic elements will be mandatory to accommodate the wide input voltage range.

The power stage specifications for this converter are determined by the power rating of the electric generator and the battery bank voltage. The operating parameters of the generator and the converter at optimal power transfer to the battery bank are calculated based on a steady-state model.

V_{in}=rectified generator voltage=75V to 600V

V_{out}=nominal battery bank voltage=240V

P=generator output power=50W to 15kW

The power-electronic switch of choice is a high-speed, high-efficiency IGBT with a maximum switching frequency above 20kHz. The free-wheel power diode needs to be a super-fast recovery device.

The ripple in the inductor current is determined by the size of the inductor and the switching frequency. The output of the wind turbine generator, in which the optimal power increases with the cube of the wind speed, puts an interesting requirement on the inductor. At increased power levels the necessary inductance for a given current ripple as a fraction of the average current is decreased. The converter operation can be scaled such that a higher current ripple is tolerated at light load.

As mentioned before a very important design issue is to minimize the parasitic elements in the power circuit connections of the DC/DC converter. Because of the very high di/dt any leakage inductance will cause voltage spikes across the semiconductor elements at the turn-on and turn-off instants of the IGBT. Wiring connections between converter and battery bank can be several feet long. To prevent voltage spikes at the switching instants, the input and output capacitors have to be mounted as close as possible to the IGBT and the diode respectively, effectively minimizing the parasitic inductance. To reduce the electro-magnetic interference (EMI) and to suppress the switching transients, a laminar bus structure was used to make the power circuit connections. To further protect the IGBT from voltage spikes a clamp-type snubber is included across its terminals.

The converter control system includes an analog control circuit receiving a signal from a software control loop implementing the Peak Power Tracker algorithm. The algorithm generates a target duty-cycle based on measurements of AC power output and alternator frequency and on the maximum rotor power curve of the turbine (Fig.4).

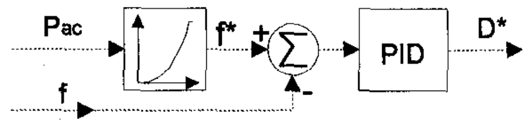

Fig. 4 Peak Power Tracker controller block diagram

The analog control circuit translates the analog voltage level proportional to the desired duty cycle into the appropriate gate signal for the IGBT. In addition it provides protection against over- and under-voltage and over-current conditions of the battery bank and shuts the converter down upon detection of a short-circuit in the IGBT.

IV. TEST SET UP

The Peak Power Tracking system is tested in conjunction with a variable-speed permanent-magnet generator and a battery bank simulator (Fig.5). The generator is driven by a dynamometer that consists of a DC motor and a gearing system. To be able to characterize the performance of the Peak Power Tracker with a constant load voltage, the battery bank is simulated with DC power supply in parallel with a resistive dump load. The voltage of a real battery bank will vary depending on state of charge and charging rate. Moreover, at high states of charge a real battery bank may not be able to absorb the full power output of the wind turbine.

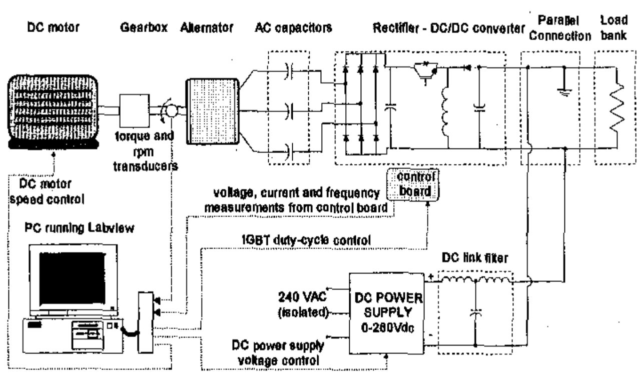

Fig. 5 test set up

The Peak Power Tracking control algorithm is implemented in Labview™ running on a PC. The program also controls the dynamometer speed effectively simulating a wind power driven rotor and performs data-acquisition of the relevant operating parameters of the system at the various stages of power conversion.

V. TEST RESULTS

For the purpose of comparing the PPT with conventional systems all test are repeated with the wind turbine generator connected to the battery bank simulator through a passive diode rectifier. The data presented are the results of tests conducted during steady state operation. The dynamometer is controlled to simulate the same conditions of rpm and torque exerted on the rotor blades at a certain wind speed. The control algorithm is then allowed to establish an optimal operating point.

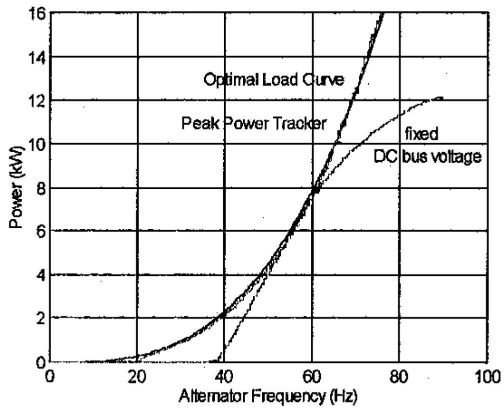

Fig. 6 Test results: steady-state power curves vs. generator frequency

The system with PPT starts to produce power, and hence charge the battery bank at 10Hz while the cut-in frequency of the system with a fixed DC bus voltage of 240V is 38Hz. The cut-in frequency corresponds to a cut-in wind speed at a certain power coefficient C_p thus there is a wind speed range where wind turbines equipped with a PPT will generate power while in existing systems the turbine just idles. The PPT-equipped system tracks the target power curve in the lower frequency range (10-55Hz) and extracts maximum power from the wind turbine generator. At higher frequencies the power-limiting effect of the increasing impedance of the generator stator leakage inductance is neutralized by the series capacitors and the OVC is able to maintain the generator's output power at the peak power operating point. At approximately 14kW the rated current of the generator is reached and the control strategy of the converter is changed to a constant-current control-mode.

In the uncompensated system the AC voltage (voltage before rectification) is clamped by the constant DC bus voltage. In contrast, the voltage vs. frequency curve of the configuration with PPT in varies approximately linearly with frequency, indicating that the control system effectively achieves constant V/f control of the generator (Fig. 7).

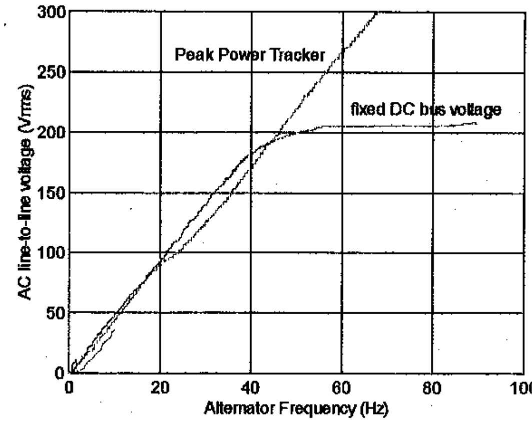

Fig. 7 Test results: AC line-to-line voltage vs. generator frequency

The current limiting effect of the generator synchronous impedance is illustrated by the declining slope of the AC line current curve of the basic system (Fig.8).

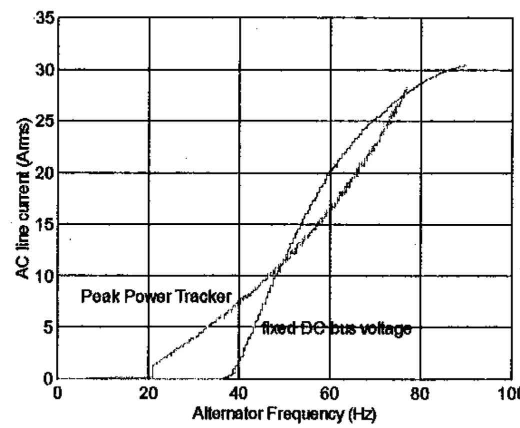

Fig. 8 Test results: Generator phase currents vs. generator frequency

The current in the generator in the system with PPT is higher than in the uncompensated system at lower frequencies because it follows the maximum rotor power curve. In the higher frequency range (from 55Hz to 70Hz) the generator current in the system with the Peak Power Tracker is comparable to that in the system with fixed DC bus voltage. However the output power charging the battery bank is considerably higher in the system equipped with a Peak Power Tracker. E.g. at 70Hz the output power of the optimized system is around 11.7kW while the basic configuration produces only 8.0kW. With the wind turbine used during the tests the Peak Power Tracker was able to boost the maximum power output of the system up to 14kW before hitting the generator current limit.

VI. CONCLUSIONS

The results provide a proof-of-concept and indicate that the Peak Power Tracker has the potential to be a significant development in small wind turbine technology. The substantial improvement of the power curve by installing a Peak Power Tracker, particularly over the upper half of the wind speed operating range, has a profound impact on the annual energy capture of the wind turbine. It is projected that an increase in annual energy capture could range from 30% to 50% in good wind sites (average wind speeds 5.5 to 7 m/s). The lower cut-in wind speed of the system means there will be charge current flowing into the battery bank even during periods of low wind speeds. This could extend the time the hybrid power system is able to run on its renewable energy sources before having to resort to the diesel generator. Performance gains of this magnitude will have a major impact on the economics of small wind turbines in battery charging applications.

The Peak Power Tracker approach is applicable to any permanent magnet generator in a battery charging application. The significant performance gains we have demonstrated are essentially independent of the specific model of generator or battery bank voltage. This allows for retrofitting of existing systems: by outfitting the wind turbine with a Peak Power Tracker, maximum power will be extracted from the rotor, provided that the generator power capability is boosted by the right amount of reactive compensation and a converter of the required power rating.

Given the fact that small wind turbines are designed for robustness and are expected to operate with little or no maintenance, it is very important that Peak Power Tracker systems have high reliability and long life expectancy.

The system will be tested with a Labview™-based control algorithm to establish the Peak Power Tracker's frequency response and dynamic peak power tracking capability. The control algorithm can then be tuned as necessary. In a final phase of the project the Peak Power Tracker will be installed on a turbine at a site with multiple turbines of the same type, all exposed to the same wind resources. This would allow a side-by-side comparison of the system with and without the Peak Power Tracker.

VII. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from the U.S. Department of Energy.

Also, the advice of Professor Lipo on the construction of the converter was highly appreciated. Finally we would like to thank Eduard Muljadi and Brian Gregory of the NREL National Wind Technology Center for advice and guidance on power electronic related problems.

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BIOGRAPHICAL INFORMATION

Alex De Broe graduated from the University of Ghent (Belgium) in 1995 as a Burgerlijk Werktuigkundig en Elektrotechnisch Ingenieur (M.Sc.E.E.). In 1997 he obtained a M.S. degree in Electrical Engineering Department from the University of Wisconsin-Madison.

He worked at the Wind Technology Division of the National Renewable Energy Laboratory on the design, implementation and testing of a controller/converter for small wind-turbine generators in battery charging applications.

Currently he is with the Netherlands Energy Research Foundation (Petten, The Netherlands). As a research engineer he is involved in the design and optimization of PV system technology. Alex De Broe's current interests include applications of control circuits and power-electronics in renewable energy technologies.

Steve Drouilhet received a B.S.M.E. from Brown University (Providence, Rhode Island), a M.S. from the Von Karman institute for Fluid Dynamics (Rhode-St.-Genese, Belgium), and a Master of Engineering from the University of California at Berkeley.

He participated as a field test engineer in the development of he first Californian wind farm in the early 1980s. He also has experience developing industrial machinery and control systems for the vacuum coating and animal feed production industries. Since joining the National Renewable Energy Laboratory in 1994, he has focused on wind-diesel hybrid power system development and has managed several small wind turbine applications development projects, including the Peak Power Tracker.

Vahan Gevorgian graduated from the Yerevan Polytechnic Institute (Armenia) in 1986. During his studies he concentrated on electrical machines. His thesis research dealt with double-fed induction generators for stand-alone power systems.

He obtained his Ph.D. degree in Electrical Engineering Dept. from the State Engineering University of Armenia in 1993. His dissertation was devoted to a modeling of electrical transients in large wind turbine generators.

Vahan Gevorgian is currently working at the National Wind Technology Center (NWTC) of National Renewable Energy Laboratory (NREL) in Golden, Colorado, USA, as a research engineer.

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