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# DESIGN OF A MAXIMUM POWER TRACKING SYSTEM FOR WIND ENERGY-CONVERSION APPLICATIONS

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***Abstract*—A wind-generator (WG) maximum-power-point-tracking (MPPT) system is presented, consisting of a high-efficiency buck-type dc/dc converter and a microcontroller-based control unit running the MPPT function. The advantages of the proposed MPPT method are that no knowledge of the WG optimal power characteristic or measurement of the wind speed is required and the WG operates at a variable speed. Thus, the system features higher reliability, lower complexity and cost, and less mechanical stress of the WG.**

**Experimental results of the proposed system indicate near-optimal WG output power, increased by 11%–50% compared to a WG directly connected via a rectifier to the battery bank. Thus, better exploitation of the available wind energy is achieved, especially under low wind speeds.**

***Index Terms*—Buck converter, maximum power point tracking(MPPT), microcontroller, variable speed, wind generator (WG).**

## I. INTRODUCTION

WIND GENERATORS (WGs) have been widely used both in autonomous systems for power supplying re-mote loads and in grid-connected applications. Although WGshave a lower installation cost compared to photovoltaics, the overall system cost can be further reduced using high-efficiency power converters, controlled such that the optimal power is acquired according to the current atmospheric conditions.

The WG power production can be mechanically controlled by changing the blade pitch angle [1]. However, WGs of special construction are required, which is not the usual case, especially in small-size stand-alone WG systems.

A commonly used WG control system [2]–[4] is shown in Fig. 1(a). This topology is based on the WG optimal power ver-sus the rotating-speed characteristic, which is usually stored in a microcontroller memory. The WG rotating speed is measured; then, the optimal output power is calculated and compared to the actual WG output power. The resulting error is used to control a power interface. In a similar version found in [5], the WG output power is measured and the target rotor speed for optimal power generation is derived from the WG optimal power versus rotor-speed characteristic. The target rotor speed is compared to the actual speed, and the error is used to control a dc/dc power converter. The control algorithm has been implemented in LabVIEW running on a PC.

In permanent-magnet (PM) WG systems, the output current and voltage are proportional to the electromagnetic torque and rotor speed, respectively. In [6] and [7], the rotor speed is calculated according to the measured WG output voltage, while the optimal output current is calculated using an ap-proximation of the current versus the rotational-speed optimal characteristic. The error resulting from the comparison of the calculated and the actual current is used to control a dc/dc converter.

The disadvantage of all above methods is that they are based on the knowledge of the WG optimal power charac-teristic, which is usually not available with a high degree of accuracy and also changes with rotor aging. Another ap-proach using a two-layer neural network [8] updates online the preprogrammed WG power characteristic by perturbation of the control signals around the values provided by the power characteristic. However, under real operating conditions where the wind speed changes rapidly, the continuous neural-network training required results in accuracy and control-speed reduction.

A control system based on wind-speed measurements [2] is shown in Fig. 1(b). The wind speed is measured, and the required rotor speed for maximum power generation is com-puted. The rotor speed is also measured and compared to the calculated optimal rotor speed, while the resulting error is used to control a power interface.

Implementations of fuzzy-logic-based control systems trans-ferring the maximum power from a wind-energy-conversion system to the utility grid or to a stand-alone system have been presented in [9] and [10], respectively. The controllers are based on a polynomial approximation of the optimal power versus the wind-speed characteristic of the WG.

Apart from the accuracy reduction due to the approximation of the WG characteristics, an accurate anemometer is required for the implementation of the aforementioned methods, which increases the system cost. Furthermore, due to wind gusts of low-energy profile, extra processing of wind-speed measure-ment must be incorporated in the control system for a reliable computation of the available wind energy, which increases the control system complexity.

In this paper, an alternative approach for WG maximum-power-point-tracking (MPPT) control is described. The block diagram of the proposed system is illustrated in Fig. 2. The MPPT process is based on monitoring the WG output power using measurements of the WG output voltage and current and directly adjusting the dc/dc converter duty cycle according to the result of comparison between successive WG-output-power values. Thus, neither knowledge of the WG power.

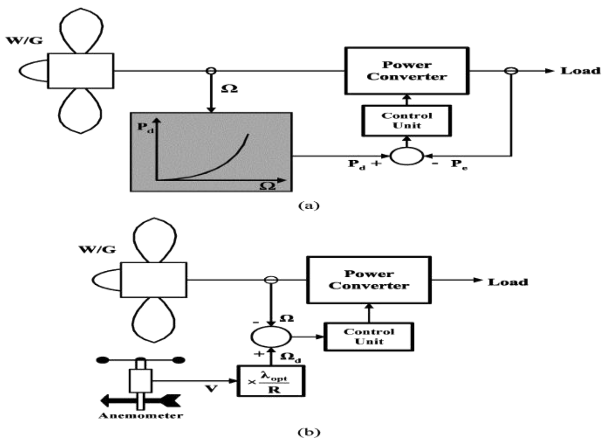



Fig. 1. WG MPPT methods. (a) Control system based on rotating-speed measurements. (b) Control system based on wind-speed measurements.

versus the rotor speed of rotation or wind-speed characteristic nor measurements of the wind speed are required. A resistive dummy load is used to protect the WG from over-speeding. The proposed MPPT method does not depend on the WG wind and rotor-speed ratings or the dc/dc converter power rating. Although the proposed method has been tested on a battery-charging application using a dc/dc converter, it can also be extended in grid-connected applications by appropriate modification of the dc/ac inverter control. The proposed system is built around a high-efficiency dc/dc converter and a low-cost microcontroller unit, which can easily perform additional operations such as battery charging management and/or control of additional renewable energy sources (RES).

This paper is organized as follows. The WG characteristics are described in Section II, the proposed system is analyzed in Section III, and the theoretical and experimental results are presented in Section IV.

## II. WG CHARACTERISTICS

The power captured by the WG blades $P_m$ is a function of the blade shape, the pitch angle, and the radius and the rotor speed of rotation

$$P_m = \frac{1}{2}\pi\rho C_p(\lambda, \beta)R^2V^3 \qquad (1)$$

where $\rho$ is the air density (typically 1.25 kg/m$^3$), $\beta$ is the pitch angle (in degrees), $C_p(\lambda, \beta)$ is the wind-turbine power coefficient, $R$ is the blade radius (in meters), and $V$ is the wind speed (in m/s). The term $\lambda$ is the tip-speed ratio, defined as

$$\lambda = \frac{\Omega R}{V} \qquad (2)$$

where **Ω** is the WG rotor speed of rotation (rad/s).

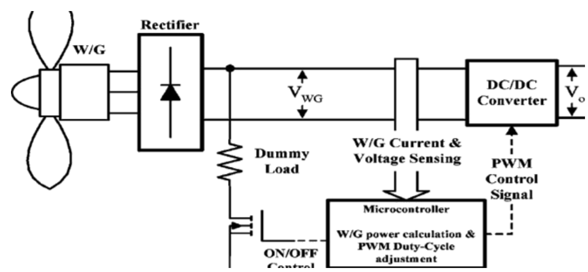
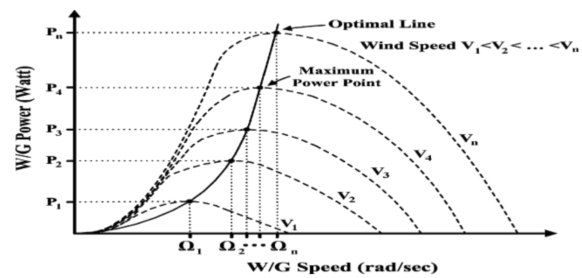



Fig. 2. Block diagram of the proposed system.

Considering the generator efficiency, the total power produced by the WG $P$ is:

$$P = \eta_G P_m. \qquad (3)$$




Besides the optimal energy production capability, another advantage of variable-speed operation is the reduction of stress on the WG shafts and gears, since the blades absorb the wind torque peaks during the changes of the WG speed of rotation. The disadvantage of variable-speed operation is that a power conditioner must be employed to play the role of the WG ap-parent load. However, the evolution of power electronics helps reduce the power-converter cost and increase its reliability, while the higher cost is balanced by the energy production gain.

The torque curves of the WG, consisting of the intercon-nected wind-turbine/generator system, for various generator output voltage levels under various wind speeds, are shown in Fig. 4. The generator is designed such that it operates in the approximately linear region corresponding to the straight portion of the generator torque curves in Fig. 4, under any wind-speed condition. The intersection of the generator torque curve with the wind-turbine torque curve determines the WG operating point. During the MPPT process, a change of the WG apparent load results in variable generator output voltage level; thus, the generator torque is adjusted such that the generator operates at the target torque (e.g., point A) under any wind speed. The target-torque line corresponds to the optimal-power-production line indicated in Fig. 3, where the energy extracted from the WG system is maximized.

III. PROPOSED SYSTEM

*A. MPPT Algorithm*

As mentioned in Section I, the MPPT process in the proposed system is based on directly adjusting the dc/dc converter duty cycle according to the result of the comparison of successive WG-output-power measurements. Although the wind speed varies highly with time, the power absorbed by the WG varies relatively slowly, because of the slow dynamic response of the interconnected wind-turbine/generator system. Thus, the problem of maximizing the WG output power using the con-verter duty cycle as a control variable can be effectively solved using the steepest ascent method according to the following control law:

$$D_k = D_{k-1} + C_1 \cdot \frac{\Delta P_{k-1}}{\Delta D_{k-1}} \quad (5)$$

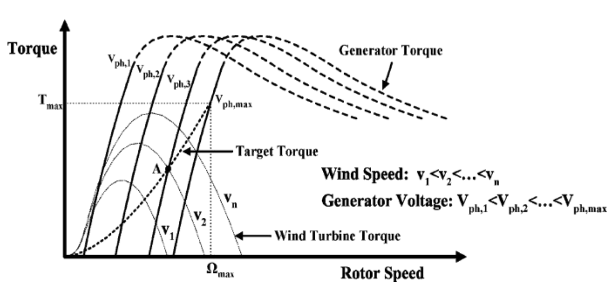



Fig. 4. Torque–speed characteristics of the wind turbine and the genera

where $D_k$ and $D_{k-1}$ are the duty-cycle values at itera-tions $k$ and $k-1$, respectively ($0 < D_k < 1$); $\Delta P_{k-1}/\Delta D_{k-1}$ is the WG power gradient at step $k-1$; and $C_1$ is the step change.

In order to ensure that this method results in convergence to the WG MPP at any wind-speed level, it is adequate to prove that the function $P$ ($D$), relating the WG power $P$ and the dc/dc converter duty cycle $D$, has a single extreme point coinciding with the WG MPPs depicted in Fig. 3.

The rectifier output voltage $V_{WG}$ is proportional to the gener-ator phase voltage $V_{ph}$; considering Fig. 4, it is concluded that

$$\frac{dV_{ph}}{d\Omega_e} > 0 \quad (10)$$

and

$$\frac{dV_{WG}}{d\Omega_e} > 0. \quad (11)$$

Considering (7)–(11), it holds that:

*dp=0*

Thus, the function $P$ ($D$) has a single extreme point, coinciding with the WG MPP, and the dc/dc converter duty-cycle adjust-ment according to the control law of (5) ensures convergence to the WG MPP under any wind-speed condition.

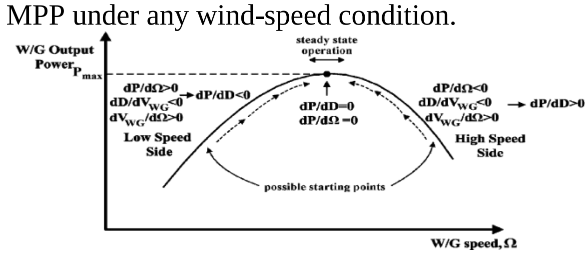



Fig. 5. MPP tracking process.

*B. Power-Electronic Interface*

The detailed diagram of the proposed system is depicted in Fig. 6. The WG ac output voltage is first converted to dc form using a three-phase full-wave bridge rectifier. The rectifier output capacitor value $C_r$ is calculated as follows:

$$C_r \geq \frac{1}{12 f R_L}\left(1 + \frac{1}{\sqrt{2}\,RF}\right) \quad (15)$$

where $R_L$ is the WG load resistance, $f$ is the WG output voltage frequency, and RF is the rectifier output voltage ripple factor.

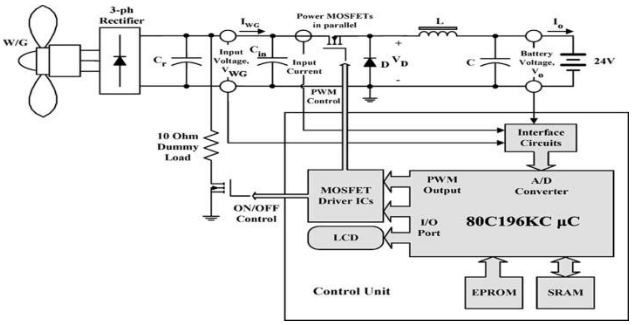



Fig. 6. Detailed diagram of the proposed system.

capability requirements. A power MOSFET is used to switch on and off a 10-Ω resistive dummy load, thus limiting the WG speed of rotation under severe conditions.

The power inductor $L$ and the input and output capacitor values, $C_{\mathrm{in}}$ and $C$, respectively, are calculated as follows [11]:

$$L \geq \frac{V_{\mathrm{om}}(1 - D_{\mathrm{cm}})}{f_s|\Delta I_{\mathrm{Lm}}|} \quad (16)$$

$$C \geq \frac{1}{8}\frac{(1 - D_{\mathrm{cm}})}{L f_s^2 \mathrm{RF_o}} \quad (17)$$

$$C_{\mathrm{in}} \geq \frac{(1 - D_{\mathrm{cm}}) I_{\mathrm{om}} D_{\mathrm{cm}}}{\mathrm{RF_{in}} V_{\mathrm{WGm}} f_s} \quad (18)$$

where $f_s$ is the dc/dc converter switching frequency, $D_{\mathrm{cm}}$ is the duty cycle at maximum output power of the converter, $\Delta I_{\mathrm{Lm}}$ is the peak-to-peak ripple of the inductor current, $V_{\mathrm{om}}$ is the maximum of the dc component of the output voltage, $I_{\mathrm{om}}$is the dc component of the output current at maximumoutput power, $\mathrm{RF_o}$ is the output voltage ripple factor (typically $\mathrm{RF_o} \leq 2\%$), $\mathrm{RF_{in}}$ is the input voltage ripple factor (typically $\mathrm{RF_{in}} \leq 2\%$), and $V_{\mathrm{WGm}}$ is the converter input voltage at maxi-mum power.

The control unit is supplied by the battery and consists of an Intel 80C196KC microcontroller unit with an external erasable programmable ROM (EPROM) and a static RAM (SRAM), the interface circuits comprising of sensors and am-plifiers connected to the on-chip A/D converter, as well as the power MOSFET IC drivers. A 39.2-kHz 8-bit-resolution on-chip pulsewidth modulation (PWM) output is used to control the power MOSFETs of the buck converter through the IR2104 driver IC, while an I/O port pin controls the power MOSFET that switches the dummy load through the IR2121 driver IC. Another I/O port is used to drive a liquid crystal display (LCD) showing various parameters of the system operation.

The WG and battery voltages are measured by means of voltage dividers interfaced to operational-amplifier (op-amp)-based voltage-follower circuits. The dc/dc converter input cur-rent is equal to the average value of the power MOSFET current, which has a pulse-type waveform and is measured with a unidirectional current transformer.

The flowchart of the control algorithm is shown in Fig. 7. The battery voltage is monitored and when it reaches a predefined set point, the MPPT operation is suspended in order to protect the battery stack from overcharging.

The PWM duty-cycle value is stored in an 8-bit register of the microcontroller, taking values that correspond to duty-cycle values 0%–99.6%. The WG output power is calculated and compared to the WG output power at the previous iteration of the algorithm. According to the result of the comparison, the sign of the duty-cycle change $\Delta D$ is either complemented or remains unchanged. Subsequently, the PWM output duty cycle is changed appropriately, thus implementing the control law described by (13).

After the duty-cycle regulation, the WG voltage is checked; if it is higher than the maximum preset limit, the dummy load is connected to the dc/dc converter input in order to protect the WG from overspeeding. The dummy load is disconnected when the WG output voltage falls below the lower preset limit. The hysteresis introduced by the maximum and minimum preset limits is necessary to avoid the dummy load continuous on/off switching.

## IV. THEORETICAL AND EXPERIMENTAL RESULTS

A prototype MPPT system was developed based on the method described above. The WG used in the experiments has a three-phase output rated at 100-V rms; thus, the dummy-load connection and disconnection voltage levels are set at 140 and 100 V, respectively.

The dc/dc converter was designed according to the methodol-ogy analyzed in Section III. The power switch consists of four MOSFETs rated at 200 V and 30 A each, while the flyback diode has a 200-ns reverse-recovery time. The calculated input and output capacitor values are 470 and 4700 $\mu$F, respectively. The output inductor value is 45 $\mu$H and is wound on a Siemens E65/21 ferrite core with a 3-mm air gap. The experimental waveform of the diode D voltage is depicted in Fig. 8. The converter operates in continuous conduction mode, and the switching frequency is approximately 40 kHz. The dc input voltage value in this case is $V_{\mathrm{WG}}$ = 66.8 V, and the dc output voltage value is $V_{\mathrm{O}}$ = 33.9 V. Such a high value of the output (battery) voltage appears in case that the battery is fully charged and sudden increase of the converter input power follows.

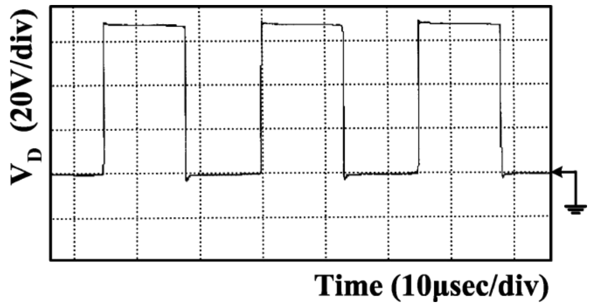



Fig 8: Experimental waveforms of DC/DC convertor diode D, voltage $V_{D.}$

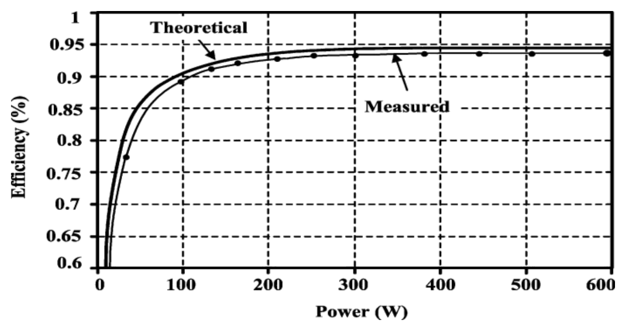



Fig. 9. DC/DC converter efficiency versus output power.

## V. CONCLUSION

In this paper, the development of a novel WG maximum power tracking control system is presented, comprising of a high-efficiency buck-type dc/dc converter and a microcontroller-based control unit. The advantages of the proposed MPPT method are as follows: 1) no knowledge of the WG optimal power characteristic or measurement of the wind speed is required and 2) the WG operates at variable speed and thus suffering lower stress on the shafts and gears compared to constant-speed systems. The proposed MPPT method does not depend on the WG wind and rotor-speed ratings nor the dc/dc converter power rating.

Experimental results of the proposed system indicate that the WG output power is increased by 11%–50%, compared to the case where the WG is directly connected via a rectifier to the battery bank. The proposed method results in a better exploitation of the available wind energy, especially in the low wind-speed range of 2.5–4.5 m/s, where the power production of the battery-rectifier configuration is relatively low. The proposed method can be easily extended to include battery charging management or additional RES control, while it can also be modified to control a dc/ac converter in the case of a grid-connected wind-energy-conversion system.

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