MAXIMUM POWER EXTRACTION IN WIND ENERGY SYSTEM WITH PITCH ANGLE CONTROL BY BOOST CONVERTER

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ABSTRACT:
This paper describes a 4-phase interleaved boost converter in a small wind turbine application. The boost converter is placed between the wind turbine and the load and is controlled to extract the maximum power from wind turbine. The boost converter duty ratio adjusted, based on the wind speed and rotor speed values, so that the wind turbine would be operated at the optimum tip speed ratio (TSR). A Field Programmable Gate Array (FPGA) based digital control system is adopted for converter control, with discontinuous conduction mode (DCM) control strategy, so that it is not necessary to actively balance the current on each phase. The modeling of the wind turbine system as well as power converter is studied by simulating analysis in MATLAB/SIMULINK, and the corresponding hardware is designed for validation. Both results show that the proposed system design has high energy conversion efficiency, with simple but reliable control strategy.
Keywords-wind turbine; interleaved boost converter; DCM; FPGA.

I. INTRODUCTION

Small wind turbines have a great potential to generate electricity for applications in rural areas, such as residences far from a power grid, telecommunication towers, monitoring stations, and places with limited electrical service. In wind generation the output power varies with rotation speed at any given wind speed. Therefore, a design to maximize the power output from existing wind turbines, in order to effectively improve the conversion efficiency is the object of recent research.

Theoretically, the wind generation power can be mechanically controlled by changing the blade pitch angle. However, this control strategy is not appropriate for small wind turbines, due to the mechanical complexity. A common method is using power electronic converters to maximize the output power from wind turbine [1-3].

This paper proposes the design of a high efficiency boost converter for maximum power extraction from a small wind turbine system, designed for battery charging (as load), and operated in a stand-alone condition.

Fig. 1 gives the block diagram of this system as well as the control strategy. The output from the turbine is a variable DC voltage (less than 48V) and the battery bank voltage is 48V. Both wind speed and rotor speed (turbine speed) are measured and utilized as input signals in the control strategy, which determines the optimal rotor speed to maximize the power extraction from the wind turbine at any measured wind speed. In the control strategy, the actual rotor speeds are compared to the computed optimal rotor speeds, and the difference values are then used to control the boost converter power delivered for battery charging.

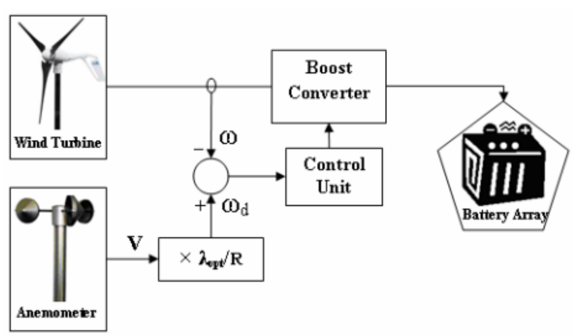

Fig. 1. The block diagram of a wind turbine control system.

Interleaving of converters is paralleling a small number of converters and operating them with a relative phase shift. The input and output current of each phase are added and their ripple is reduced and harmonic reduction is achieved. The capacitor losses will be reduced since the RMS current in the capacitor is reduced due to the reduction in capacitor ripple current, and the converter efficiency will also be improved. Also the inductance and capacitance can be reduced significantly as the number of phases is increased. In some applications, it is possible to make change from polymer organic or tantalum capacitors to ceramic capacitors that will improve the equivalent series resistance and power density. The size and cost could also be reduced. Further since each phase processes a part of the total power, the switch component stresses will be reduced.

There are two main issues for design of an interleaved converter. One is the generation of the shifted control pulses with high accuracy as the number of phases is increased. This can be solved by the use of digital controllers built in specific hardware such as a Field Programmable Gate Array (FPGA) [4]. Another is the current balance on each phase, especially when the converter operated in continuous conduction mode (CCM) [5, 6].

In this paper, a 4-phase interleaved boost converter is used, which operates in discontinuous conduction mode (DCM). Under DCM operation, active control of the current balance can be ignored [7]. The digital control signals are generated from a (FPGA) system, programmed with LabVIEW.

The simulation model of wind turbine control system is discussed in this paper. The 4-phase interleaved boost converter hardware is also developed and tested for validation, with the test results presented.

Compared with similar designs, the boost converter developed in this paper has the following advantages: 1) High energy conversion efficiency; 2) Reduced current ripple; 3) Simple but reliable control method; 4) Small filter and a better dynamic response.

II. METHODOLOGY

A. Wind Turbine Characteristics

The mechanical power developed by a wind turbine is:

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

Where ρ is the air density (typically 1.25 kg/m3), A is the swept area (m2), β is the pitch angle (degrees), Cp(λ, β) is the power coefficient of wind turbine, V is the wind speed (m/s). The term λ is the tip speed ratio, which is defined by:

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

Where ω is the wind turbine rotor speed of rotation (rad/s), R is the blade radius (m).

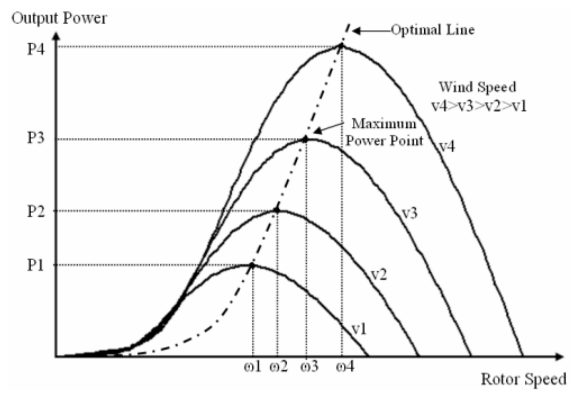

Fig. 2. Output power versus rotor speed at various wind speeds.

The output power of the turbine can be formulated as a function of the power coefficient of the turbine at a constant wind speed. And the power coefficient is maximized for tipspeed ratio value λopt at a given pitch angle. The turbine power curves for various wind speeds are provided in Fig. 2. For each wind speed, a specific point exists where the maximum power can be captured. In order to extract maximum power, the rotor speed must be held at its optimal tip-speed ratio. The optimum speed of rotor can be estimated as follows [1]:

$$\omega_{opt} = \frac{\lambda_{opt} V}{R} \qquad (3)$$

B. Design of Boost Converter

Interleaved converters are achieved by parallel connecting each phase arm of a converter, sharing common bus capacitors. The schematic diagram of a 4-phase interleaved converter is shown in Fig. 3.

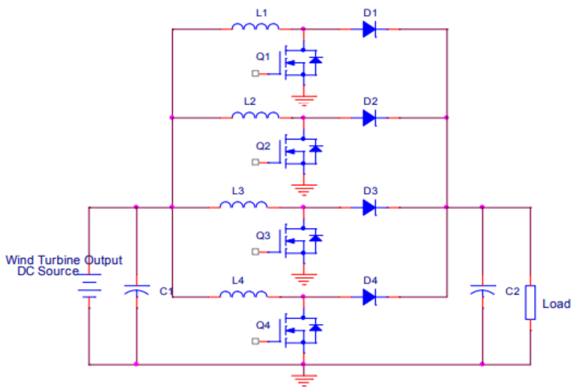

Fig. 3. Schematic diagram of 4-phase interleaved boost converter.

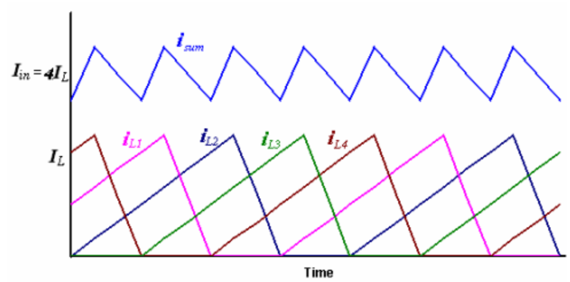

Fig. 4. Input current and inductor current waveforms of a boost converter operating in DCM.

The switching signals from each phase arm are phase shifted by 90 degrees in time. Each phase processes only 1/4 of the total power. The inductor current and their sum current waveforms are shown in Fig. 4. As can be seen, the inductor current of each phase is interleaved by 900 . The current Iin = IL1 + IL2 + IL3 + IL4 is from discharge of the input capacitor as well as generator of the wind turbine. The amplitude of Iin ripple is much smaller than any individual inductor current. Actually, the output current ripple will also be reduced significantly. Generally, increasing the number of phases will decrease the current/voltage ripple. However, increasing the phases also results in an increased number of switches (IGBTs are used in this paper), which may increase the loss of energy and decrease the efficiency. Also it will increase the complexity of the circuit and control of the converters. The optimum number of phases is dependent on the converter parameters such as the phase inductance and operating requirements [8, 9].

One phase is dedicated to be the master whose duty ratio will be controlled by the system, and other phases are slaves, each of those control signals are shifted 2nπ/N from the master phase (N is the number of phase, n = 1, 2, …, N-1). The control of battery charging power can result in variable rotor speed operation, such that maximum power is extracted continuously from the wind. This control for maximum power in this paper is based on directly adjusting the boost converter duty cycle according to the result error of comparison of rotor speed.

In the control of a converter, there are two algorithms popularly used, discontinuous conduction mode (DCM) and continuous conduction mode (CCM). A study comparing the performance of CCM and DCM shows that, DCM is a more preferable selection in practice than CCM [7]. From [7], in CCM, a relative small duty cycle deviation will result in unacceptable current unbalance among phases, while DCM current unbalance is lower since each phase current starts from zero every switching cycle. If the CCM algorithm is chosen, the duty cycle should be very precise, and it is better to include one current control loop per phase which will increase cost. Therefore, the DCM algorithm is selected in this paper, for controlling of the interleaved converter. In the DCM operation, the current ripple in each phase will be large, but the current ripple going into the battery can still be small because of the multi-phase interleaved converter.

III. SIMULATION RESULTS

To demonstrate the performance of the interleaved boost converter for a wind turbine application, the wind turbine system and interleaved boost converter are simulated in MATLAB/Simulink before the circuit is developed. The whole system model is shown in Fig. 5.

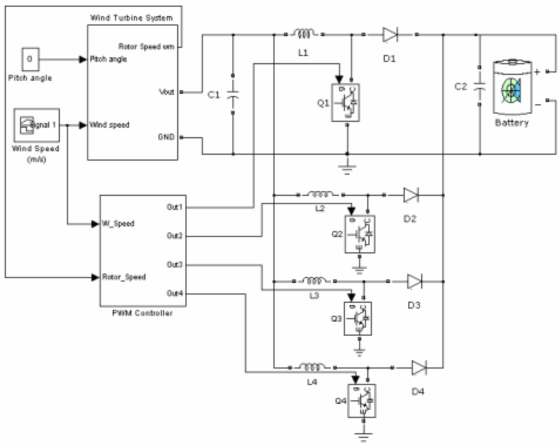

Fig. 5. The model of maximum power extraction from wind turbine system.

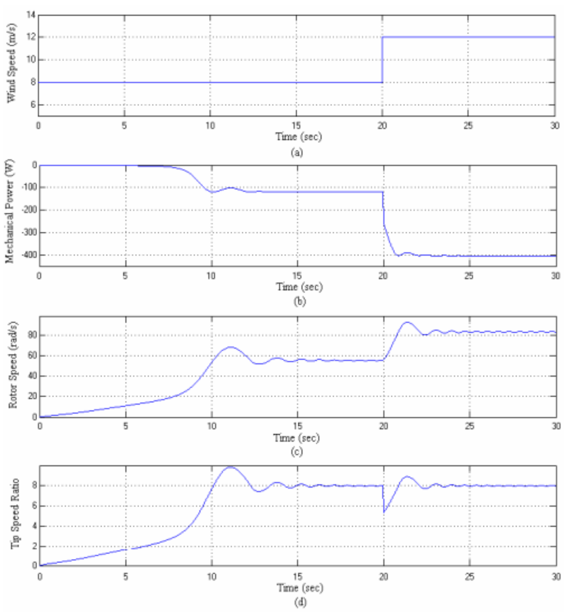

Fig. 6. (a) Wind speed. (b) Mechanical power from turbine (c) Rotor rotational Speed. (d). Tip Speed Ratio.

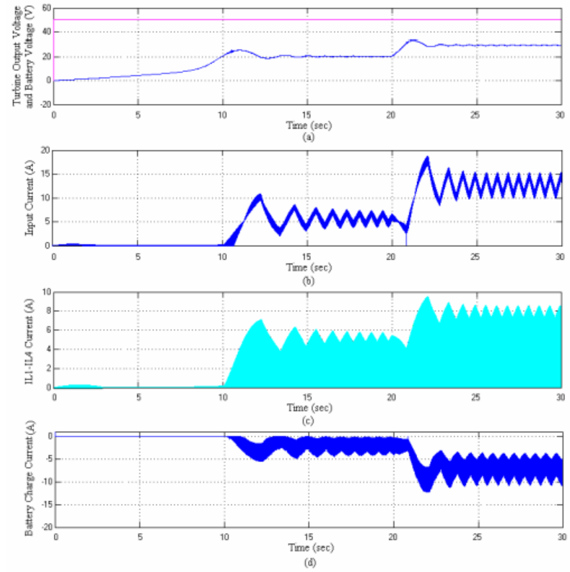

Fig. 7. (a) Wind turbine output voltage vs battery charging voltage (~50V). (b) Input current (sum of 4-phase inductor current) (c) Inductor currents in 4-phases. (d) Battery charging current.

In this model, the output of the wind turbine system in the model is a dc voltage, and then the power is used for charging the battery through a 4-phase interleaved boost converter. A PWM controller is designed to generate control signals for each switch device to ensure that the tip speed ratio is held to 8. A wind speed starting at 8 m/s with a step increase from 8 to 12 m/s at 20 seconds is applied to this model as input, and the waveform is shown in Fig. 6 (a). The simulation results are shown in Fig. 6 (b) ~ (d) and Fig. 7. At beginning, the system need approximately 12 seconds from startup to achieve stable operation. After that, the system can response rapidly for a step change, such as the wind speed increase to 12 m/s in Fig. 6 (a). The tip speed ratio drops at first but reaches the set optimum of 8 finally.

Fig. 7 is the result for a boost converter. Fig. 7 (a) is wind turbine output voltage and battery voltage waveforms, as well as input voltage and output voltage for the boost converter. Fig. 7 (b) is the input current which equals the sum of IL1,, IL2, , IL3,and IL4. Fig. 7 (c) is the inductor current in 4 phases and Fig. 7 (d) is the battery charging current. Fig. 8 is a zoomed in view of Fig. 7. As can be seen, the current in the inductor of each phase is from 0 to 8 A and discontinuous, while the input current is 13.7 ± 0.9 A and the current for battery charging is 7.7 ± 2.6 A. Both current ripples are much smaller than the separate inductor current ripple.

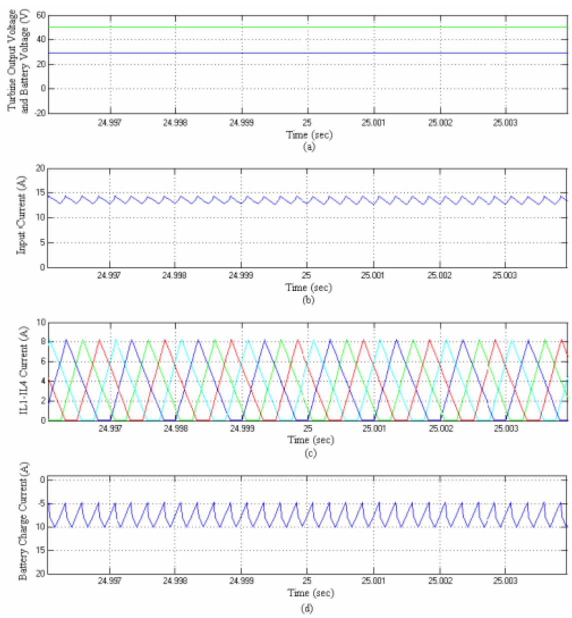

Fig. 8. Zoomed in view of Fig. 7.

IV. EXPERIMENTAL RESULTS

An isolated 4-phase interleaved boost converter has been designed and the implemented converter steps 30V up to 48V at 200W. The inductor in each phase is 50 µH. The phase switching frequency is 10 kHz and is generated by an FPGA. Fig. 9 is the switch gate drive signal and each phase is interleaved by 900 . Fig. 10 shows the inductor current waveforms in each phase. It can be seen that the amplitude of those currents is almost equal and the phase is interleaved by 900 without using any current loop for balance. Fig. 11 is the input current (the sum of inductor currents) compared with the current in one inductor. The inductor current is from 0 to 8A and discontinuous, while the input current is 7.1 ± 0.6 A. So the input current ripple is much lower than in each separate inductor.

The efficiency for this converter is 92.2% (V_in: 29.76 V; I_in: 7.07 A; V_out: 48.76 V; I_out: 3.98 A). The loss analysis data for this converter is:

- Inductors copper loss: 1.8 W
- Inductors core loss: 2.6 W
- IGBTs conduction loss: 4.6 W
- Diodes forward loss: 3.4 W
- Other losses: 3.9 W

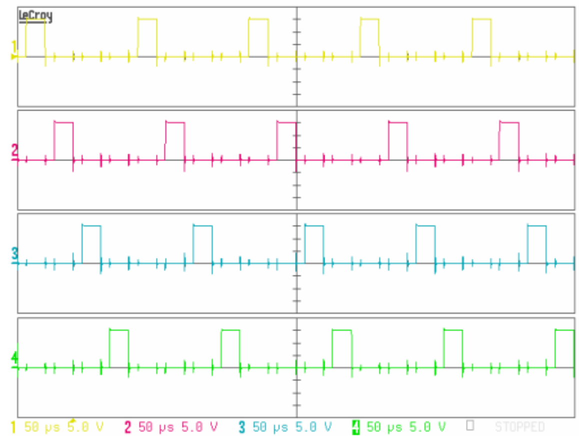

Fig. 9. Gate drive signal waveforms of 4 phases.

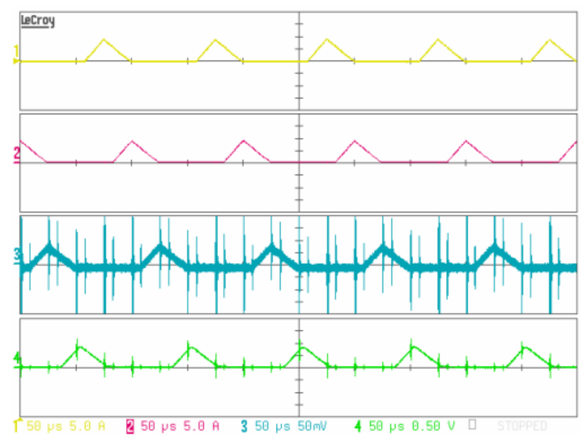

Fig. 10. Inductor current in each phase. (The last two current waveforms have more noise due to different measuring equipment)

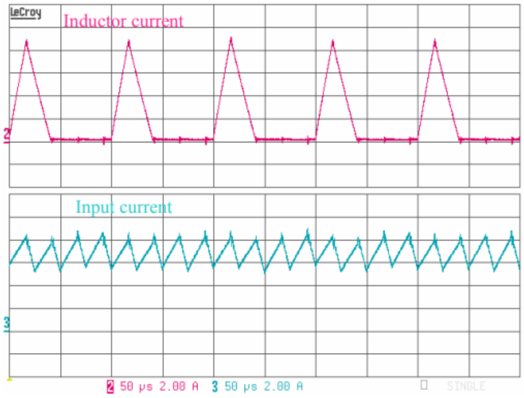

Fig. 11. One phase inductor current vs input current.

V. CONCLUSIONS

The proposed system along with required power electronics and control scheme were designed, simulated, implemented and tested. The maximum power tracking was ensured by operating the wind turbine at an optimum tip speed ratio. A real circuit of 4-phase interleaved boost converter was built and tested, with satisfactory performance achieved. This interleaved converter can be used for further research on other applications, especially for high current applications, which eliminates the use of large capacitors and inductors while achieving small current ripple and also improving the efficiency.

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