

Highly Efficient AC-DC Converter for Small Wind Power Generators

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Abstract

A highly efficient AC-DC converter for small wind power generation systems using a brushless DC generator (BLDCG) is presented in this paper. The market standard AC-DC converter for a BLDCG consists of a three-phase diode rectifier and a boost DC-DC converter, which has an IGBT and a fast recovery diode (FRD). This kind of two-stage solution basically suffers from a large amount of conduction loss and the efficiency greatly decreases under a light load, or at a low current, because of the switching devices with a P-N junction. In order to overcome this low efficiency, especially at a low current, a three-phase bridgeless converter consisting of three upper side FRDs and three lower side Super Junction FETs is presented. In the overall operating speed region, including the cut-in speed, the efficiency of the proposed converter is improved by up to 99%. Such a remarkable result is validated and compared with conventional solutions by calculating the power loss based on I-V curves and the switching loss data of the adopted commercial switches and the current waveforms obtained through PSIM simulations.

Key Words: Energy saving, High efficiency, Small wind power generator, Super Junction FET, Three-phase bridgeless converter

I. INTRODUCTION

As shown in Fig. 1, a conventional solution for a small wind power generator to get approximately DC 400V of supply, which is connected to single-phase AC 220V utility via a full-bridge inverter, from variable speed blade rotation is composed of a three-phase BLDCG, a three-phase diode rectifier, and a boost converter [1]. For comparison, a typical solution with a sinusoidal current waveform for high power rating is depicted in Fig. 2 [2]. When compared with a permanent magnet synchronous generator (PMSG) with a sinusoidal EMF voltage, a BLDCG producing a trapezoidal EMF voltage can be manufactured at a lower cost in terms of winding method and permanent magnet shaping. Considering the very cheap diode rectifier module a much lower silicon cost can be easily estimated. Moreover, the torque control for a BLDCG can be simply realized without rotor angle detection by a single PI current controller in the same manner as a boost DC-DC converter, while a three-phase PWM converter requires a rotor position sensor or an EMF voltage observer.

There are two main disadvantages to the BLDCG solution: a torque ripple and a non-unity displacement power factor. Note that the ideal current waveform of a BLDCG for constant torque is quasi-rectangular. Both of these shortcomings are due to a nonzero commutation time by the stator inductance of the BLDCG, which acts as a source inductance. Nevertheless, most small wind power generators adopt the BLDCG solution because the market demands low price rather than high

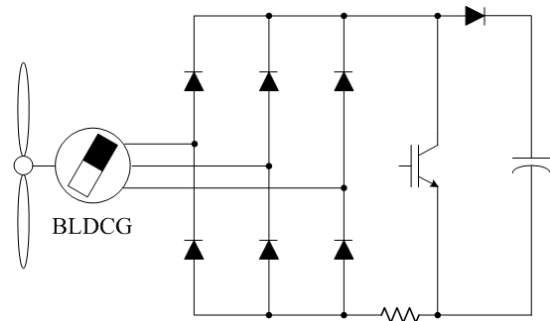


Fig. 1. Conventional small wind power generation system.

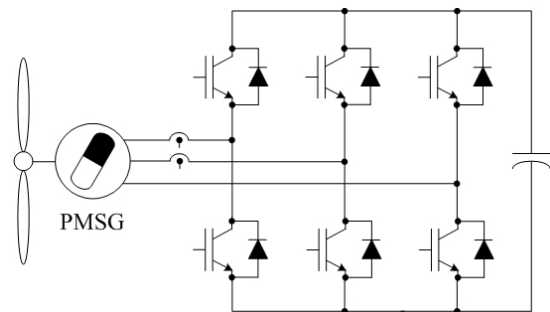


Fig. 2. Typical wind power generation system for high power rating.

performance or high efficiency.

However, the growing recognition of energy saving will drive market products to higher efficiency and it has already begun in some markets. For example, in Europe's solar inverter market higher efficiency has been acting as an important marketing factor. Not only maximum efficiency measured with the rated output power but also European efficiency, in which the

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power variation is taken into account with weighting factors reflecting actual operating conditions, should be evaluated and specified [3]. This new criterion for efficiency benchmarking helps consumers make the right choice for substantial energy savings. Consequently, progressive solutions for higher efficiency such as Sunways' HERIC topology [4], SMA's H5 topology [5], and Vincotech's power module FZ06BIA045FH using SiC Schottky diodes and Super Junction FETs [6] have been commercialized.

Another application example is Toshiba-Carrier's air conditioner, the three-phase PWM inverter of which has adopted Super Junction FETs for the three lower side switches along with a special technique to suppress a large amount of the switching loss due to poor reverse recovery of the body diode [7]. Since a Super Junction FET has a much lower conduction loss at a low current when compared to an IGBT, this solution shows a remarkably high efficiency in actual operating conditions, where most of the time is spent under a light load.

Such efforts for substantial energy saving are necessary in a power conversion system for wind power generation as well. Wind power is a cubic function of wind speed [8]. The average wind speed is normally around half of its rating, then the wind power goes down to one eighth of its rating. As a result, substantial energy saving for a wind power generator can be achieved through enhancing the efficiency at low power as well as high power.

From the viewpoint of the above-mentioned energy savings, the conventional AC-DC converter of Fig. 1 basically suffers from a large conduction loss because the current flows through three switching devices. Besides, since both the diode and the IGBT have an offset voltage due to the potential barrier of the P-N junction, the efficiency is degraded at a low current.

In this paper, a highly efficient AC-DC converter for a small wind power generation system using a BLDCG is presented. The proposed circuit topology is a three-phase version of a single-phase bridgeless converter for power factor correction (PFC) [9]-[11]. When compared with the conventional solution, the proposed one allows the current to flow only through two switches and the current itself can be lower at the same output power. In addition, by replacing the IGBTs with Super Junction FETs and utilizing synchronous rectification a further reduction of conduction loss, especially at a low current, can be achieved because Super Junction FETs are resistive without an offset voltage in the ON state. Eventually within the whole operating speed range, including the cut-in speed, the efficiency of the proposed AC-DC converter can increase by up to 99%. This result is validated and benchmarked with the conventional solution by calculating the power loss based on the conduction and switching loss data of the adopted commercial switching devices and the current waveforms obtained through PSIM simulations.

In this paper, a 3kW system with the specifications and parameters summarized in Table I is used as an example. All of the waveforms given in the figures were obtained from computer simulations using PSIM.

TABLE I
SPECIFICATIONS AND PARAMETERS OF 3kW WIND POWER GENERATION SYSTEM USING BLDCG

Rated wind speed	13.5m/sec
Blade radius	1.26m
Optimum tip speed ratio	7
Power coefficient	0.45
Rated output power	3kW
Rated rotational speed	720rpm
Minimum rotational speed (cut-in)	180rpm
Number of poles	12
Stator resistance	0.5Ω
Stator inductance	8mH
Rated EMF voltage (Line-to-line peak)	300V
DC-link voltage	400V
Switching frequency	5kHz
Current control bandwidth	2000rad/sec

II. CONVENTIONAL AC-DC CONVERTER

A three-phase BLDCG can be modeled as the following voltage equation:

$$\begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} = \begin{bmatrix} R_s + p(l_s + M) & -\frac{1}{2}pM & -\frac{1}{2}pM \\ -\frac{1}{2}pM & R_s + p(l_s + M) & -\frac{1}{2}pM \\ -\frac{1}{2}pM & -\frac{1}{2}pM & R_s + p(l_s + M) \end{bmatrix} \times \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}, \quad (1)$$

where e_{as} , e_{bs} , and e_{cs} : the three-phase EMF voltages, i_{as} , i_{bs} , and i_{cs} : the three-phase currents, v_{as} , v_{bs} , and v_{cs} : the three-phase terminal voltages, R_s : the stator resistance, l_s : the stator leakage inductance, M : the stator mutual inductance, and p : the differential operator.

Since the sum of three phase currents is always zero, Eq. (1) can be simplified as:

$$\begin{bmatrix} e_{as} \\ e_{bs} \\ e_{cs} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & 0 \\ 0 & R_s + pL_s & 0 \\ 0 & 0 & R_s + pL_s \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}, \quad (2)$$

where $L_s (= l_s + \frac{3}{2}M)$: the stator inductance.

From (2), an equivalent circuit diagram of Fig. 1 is given as Fig. 3. Note that the stator inductance of the BLDCG makes it possible to step up the output voltage, or the DC-link voltage without an additional inductor. However, the existence of the stator inductance causes a negative impact on the current commutation in the rectifier diodes, or a displacement power factor and a torque ripple, as shown in Fig. 4.

A PI feedback current controller can be designed in the same manner as a boost DC-DC converter, as shown in Fig. 5. Note that the DC-link voltage regulation is performed by a controller for a full-bridge DC-AC inverter connected to the power grid. The input DC current of the boost converter, or the output current of the diode rectifier is commanded with a maximum power point tracking (MPPT) algorithm and its feedback current can be sensed with a shunt resistor through an inverting amplifier. A simple PI feedback controller outputs the pole voltage reference, which is applied to the negative input of a triangular wave comparator for PWM. The triangular wave varies between zero and a DC-link voltage with a constant frequency. The output signal of the comparator is transferred

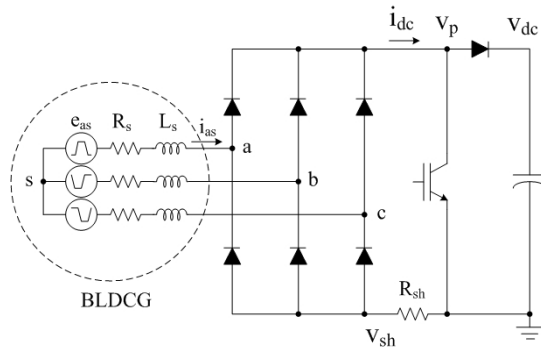


Fig. 3. Equivalent circuit diagram of the conventional small wind power generation system.

to an IGBT through a gate driver, which can provide sufficient source and sink currents for gating.

One algorithm for MPPT uses a loop-up table or a function of the input DC current of the boost converter (torque) according to the pole voltage reference (speed) [1]. Another algorithm observes the variation of the output power after perturbing the input command of current controller. This is called the perturbation and observation (P&O) method. The output power can be calculated by the product of the input DC current of the boost converter and the pole voltage reference.

As mentioned earlier, the objective of this paper is not MPPT but power loss comparison. Therefore, in this paper the output power was simply regulated to be a cubic function of the rotational speed neglecting a MPPT error due to the power loss in the BLDCG and AC-DC converter.

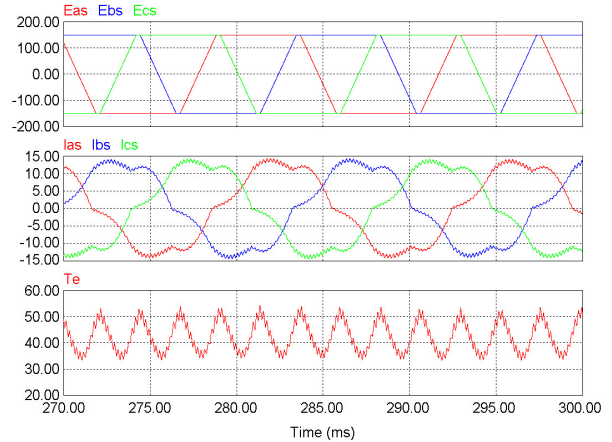
III. PROPOSED AC-DC CONVERTER

In terms of efficiency, the conventional converter has a lot of room for improvement. The first proposed solution is depicted in Fig. 6. It has been extended to a single-phase bridgeless converter for power factor correction (PFC). The upper side diodes should be a fast recovery type that takes into consideration the switching loss, while the lower side diodes should be a rectifier type with as low a forward voltage drop as possible because they are turned off unforcedly.

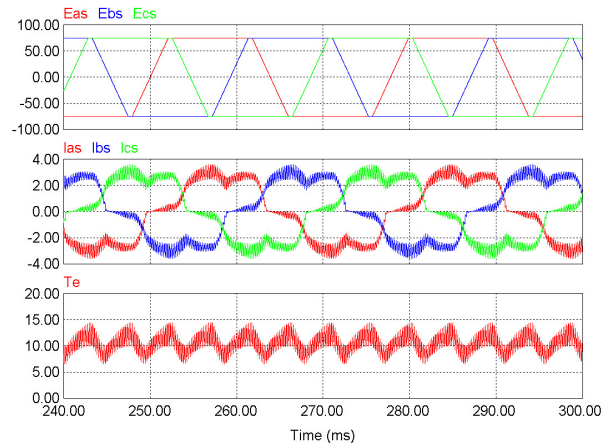
The current control method for the proposed converter is the same as the conventional one described in section II except for the switching rotation. Each IGBT is gated by PWM with a constant switching frequency during the positive 120deg interval, or when the corresponding EMF phase voltage is at its maximum and keeps the OFF state during the remaining 240deg interval. Such a switching rotation can be realized by a U/V/W signal hall-effect sensor installed inside the BLDCG in the same manner as a BLDC motor drive. Fig. 7 shows a current control block diagram of the proposed converter.

Apart from the cooling benefit due to heat dissipation spreading, the efficiency of the proposed solution can be improved by the following two differences when compared to the conventional one.

1. The number of switching components through which the current flows is reduced by one. In the conventional solution, the current flows through two rectifier diodes and one IGBT or one FRD, while the current flows through one rectifier diode



(a) At 720rpm rotational speed and 3kW output power.



(b) At 360rpm rotational speed and 375W output power.

Fig. 4. Three-phase EMF voltages and currents, and torque of the conventional small wind power generation system.

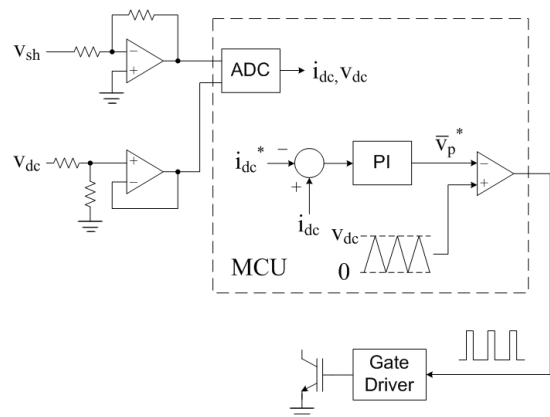


Fig. 5. Current control block diagram of the conventional small wind power generation system.

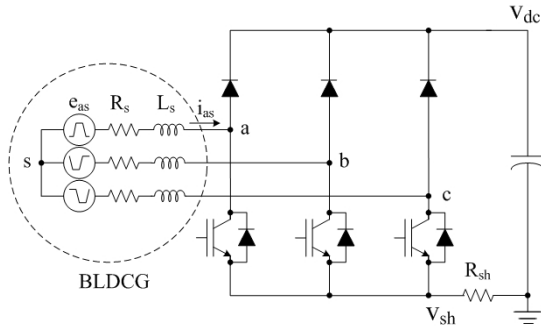


Fig. 6. Equivalent circuit diagram of the first proposed solution.

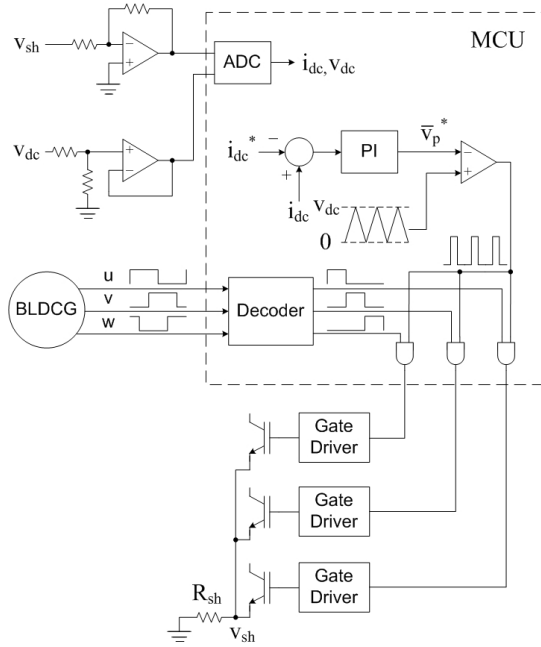


Fig. 7. Current control block diagram of the proposed solution.

and one IGBT or one FRD in the proposed solution. During current commutation one more rectifier diode conducts in both cases. As a result, the power loss can be reduced by as much as the conduction loss of one rectifier diode.

2. The RMS phase current at the same output power is smaller because the current commutation is faster. Fig. 8 shows the three-phase EMF voltages and currents under the same operating conditions as Fig. 4. Note that the current commutation is shortened when the phase current is positive, or at the so-called forced commutation, while almost the same as with the conventional solution when the phase current is negative, or naturally commutated. The difference between the forced and natural commutations is due to the potential of the previously conducting phase terminal during the current commutation. In the conventional solution, the previously conducting phase terminal is tied to the same potential (IGBT collector) with a newly conducting phase terminal as shown in Fig. 9(a). Then, the current is naturally commutated by the variation of the EMF voltage from the previously conducting phase. On the other hand, in the proposed solution, the potential of the previously conducting phase terminal has the same potential as the positive DC-link terminal, as shown in Fig. 9(b). Such a high potential enables a more rapid commutation. For example,

the RMS phase current in Fig. 4(a) and Fig. 8(a) is 9.6A and 9.2A, respectively.

As emphasized in section I, the efficiency at a small output power should be enhanced in order to achieve a substantial energy savings. This can be realized by replacing three IGBTs and three anti-parallel rectifier diodes with three MOSFETs as shown in Fig. 10. As the rotational speed, or the EMF voltage decreases, the ON duty of the MOSFET increases almost linearly. Since the output power is proportional to the cube of the rotational speed, the effectiveness of the MOSFET on the reduction of the conduction loss rapidly rises as the rotational speed decreases. Unlike the AC-DC converter in Fig. 2, the proposed solution is able to use Super Junction FETs with an ultra low ON resistance because the body diode is turned off unforcedly. In other words, the proposed bridgeless circuit does not have the large switching loss due to a poor reverse recovery of the body diode.

In addition, by making use of the so-called synchronous rectification technique a further reduction in conduction loss is attainable. Fig. 11 shows the gating signal of an a-phase MOSFET for synchronous rectification. Each MOSFET keeps ON during the negative 120deg interval, or when the corresponding EMF phase voltage is at its minimum, in rotation.

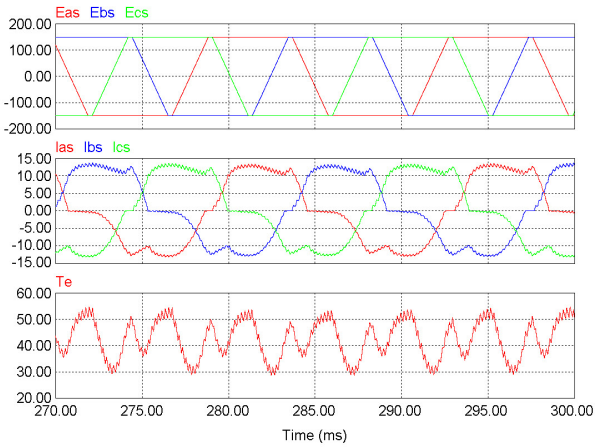
IV. POWER LOSS CALCULATION AND COMPARISON

In terms of the following four kinds of solutions, including two intermediate proposals, the power loss has been benchmarked in order to distinguish the contribution of each step in the process to get to the final goal.

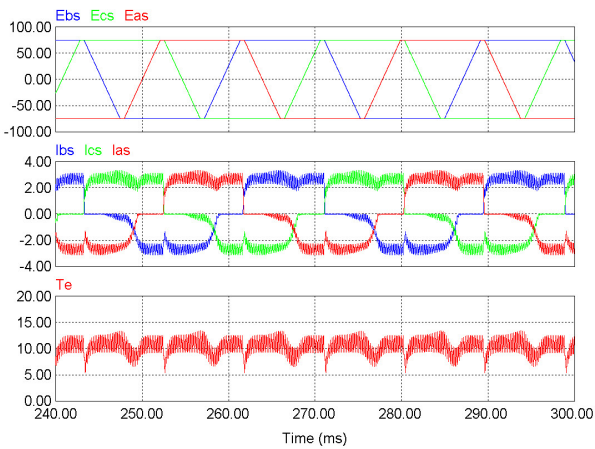
- S1. Conventional solution
- S2. Proposed solution with IGBTs
- S3. Proposed solution with Super Junction FETs
- S4. S3 + synchronous rectification

In order to measure the efficiency of the AC-DC converter itself, the terminal voltage of the BLDCG should be measured. However, it is step-changed at every switching instant, thus causing some integration error in the process of measuring the input power because of a relatively low bandwidth or sampling rate.

In this paper, in order to obtain accurate efficiency, the power loss is calculated from the conduction and switching loss data of the adopted commercial switching devices and the current waveforms. The part numbers of the switching devices used in solutions S1~4 are given in Table II. The I-V curve of each switch was referred from the datasheet provided by the manufacturers. The switching data were measured in the laboratory through a switching test that takes into consideration the combination of IGBTs or MOSFETs and FRDs corresponding to each solution. In addition, in order to reflect the temperature dependency all of the data have been adequately interpolated between 25deg and 125deg depending on the output power. The current waveforms were obtained using the PSIM simulation as shown in Fig. 4 and Fig. 8. Finally, the conduction loss was calculated by the integral of the product of the switch voltage drop and current, while the switching loss was calculated by the sum of the switching loss energy.



(a) At 720rpm rotational speed and 3kW output power.



(b) At 360rpm rotational speed and 375W output power.

Fig. 8. Three-phase EMF voltages and currents, and torque of the proposed solution.

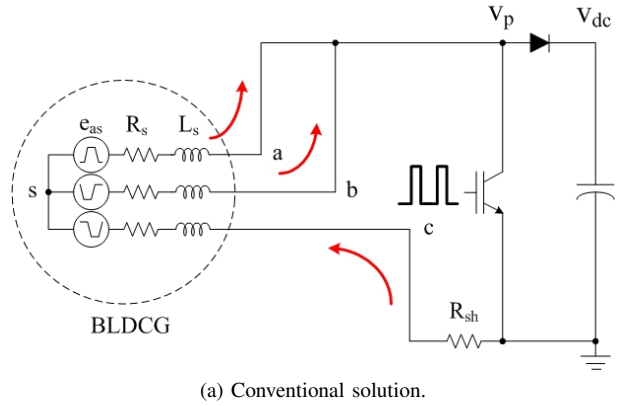
TABLE II

PART NUMBERS OF SWITCHING DEVICES USED IN SOLUTIONS S1~4.

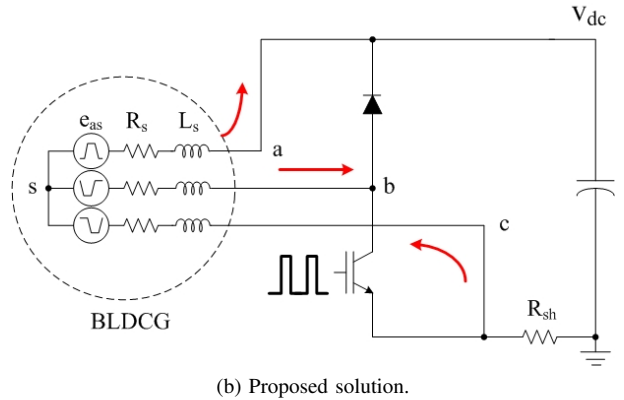
Solution	IGBT/MOSFET	Rectifier diode	FRD
S1	IGW30N60T	DF20BA80	IDP23E60
S2	IGP15N60T	FFPF30UA60S*	IDP15E60
S3, S4	FCH35N60	Not used	IDP15E60

* Since a discrete rectifier diode or an IGBT co-pack with a rectifier diode was not available, a FFPF30UA60S (Ultrafast diode) having an I-V curve similar to a 20A rectifier diode was used as an alternative.

Fig. 12 and Fig. 13 show the efficiency of solutions S1~4 according to their output power and the rotational speed, respectively. As expected, by changing the circuit topology to a bridgeless type about a 1% higher efficiency is gained, which is definitely due to the reduced number of conducted switches (S2). Moreover, the replacement of IGBTs by Super Junction FETs enables more than a 1% increase in efficiency at half of the rated speed or below (S3). Finally, by adding the synchronous rectification more than 99% efficiency is achieved in the whole operating speed region (S4). Since the average speed is normally around half the rated speed, the proposed solution can have a 1.5~2.0% higher efficiency on average in an actual operating environment when compared to the conventional solution.



(a) Conventional solution.



(b) Proposed solution.

Fig. 9. Equivalent circuit diagram during current commutation from a-phase to b-phase when a-phase current is positive.

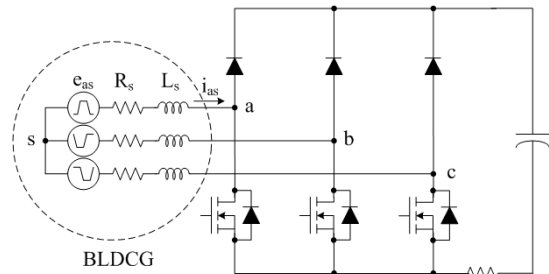


Fig. 10. Equivalent circuit diagram of the second proposed solution.

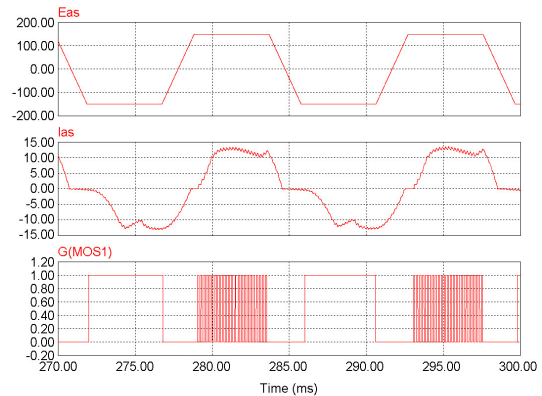


Fig. 11. Gating signal of a-phase MOSFET for synchronous rectification.

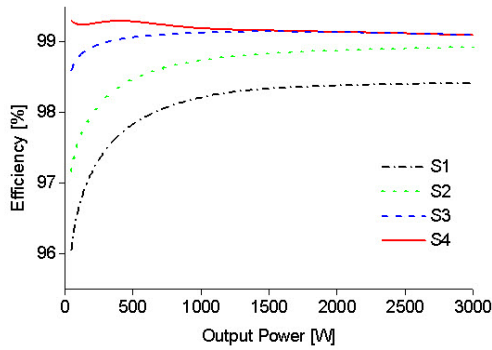


Fig. 12. Efficiency according to output power.

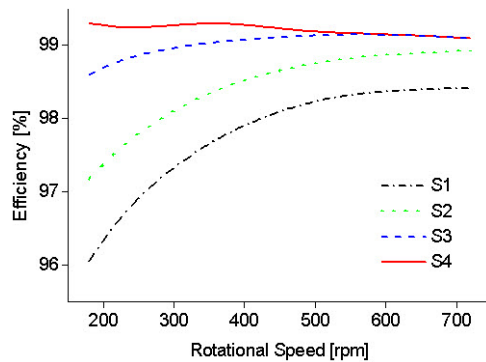


Fig. 13. Efficiency according to rotational speed.

V. CONCLUSIONS

This paper demonstrates a method for obtaining substantial energy savings for a small wind power generator with a rating below 3kW. The key idea is the combination of a bridgeless converter and a Super Junction FET with an ultra low ON resistance for minimizing the conduction loss. The result of the power loss calculation reveals that the efficiency of the proposed converter can reach 99% in the whole operating speed region. Such an outstanding result for energy savings cannot be realized with the PWM converter of a PMSG solution where a Super Junction FET is inapplicable or ineffective.

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