Efficiency improvement of a small wind turbine by adaptation of the rectifier circuit and control

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***Abstract*—Grid-connected small wind turbines are a promising technology to further increase the share of renewables in the energy supply. Although their impact on the environment is proven to be advantageous, the cost effectiveness needs to increase to favor a market breakthrough. This can be achieved with technological improvements, driven by research. The most obvious improvements can be found in the optimization of each component. However, the combination of highly efficient components does not necessarily result in an efficient system. The interactions between the subcomponents also play an important role in the total system efficiency. Therefore, the interaction between the converter and the generator will be the focus of this research. The impact of the control strategy of the converter on the generator efficiency will be explained in this paper.**

***Index Terms*—Wind energy, Permanent Magnet Synchronous Generator, Current waveform, Converter topology**

I. INTRODUCTION

A general awareness concerning the impact of fossil fuels on the environment has given a boost in the development of renewable energy technologies. Photovoltaic panels and large wind turbines already have a high market share and are technologically mature. The amount of renewable energy technologies should however be further diversified to increase the share of renewables in the energy production. Small wind turbines could play this role. The effect of small wind energy on the environment is shown to be very promising [1]. With a rated power between 1 kW and 30 kW, they are suitable for industrial and rural areas, i.e., for small and medium enterprises or agricultural companies.

Although the design of a large wind turbine can be considered as mature, it is not directly applicable for small wind turbines. The reason is the fundamental difference between small wind turbines, with a rated power below 30 kW, and large wind turbines, with a rated power above 300 kW. For instance, the wind speed is much more variable at low altitude due to the influence of the rough surface of the earth and obstructions in the vicinity (e.g. buildings or trees) [2], [3]. Also, for a small wind turbine, the cost of certain components or mechanisms becomes unacceptable in relation to the total investment cost. For example, an active pitch mechanism is not frequently implemented and a simple wind vane often forms a passive yaw mechanism. Furthermore, the inherently lower power rating of a small wind turbine implies a different generator and converter design [4].

The specific design of small wind turbines offers several technological challenges. Although there are already several small wind turbines available on the market, the cost-effectiveness can still be improved. Technological improvements, driven by research, can increase this cost-effectiveness to ensure a market breakthrough [5]. The most obvious area of improvement lies in the efficiency of the components, i.e. the turbine blades, the generator, the rectifier and the inverter. The interaction between these components should however not be underestimated. Therefore, the combination of components with a high efficiency does not necessarily result in a system with an optimal efficiency. The focus of this research is, thus, on the interactions between the components and their impact on the total efficiency.

One of these interactions is the effect of the converter control strategy and circuit topology on the efficiency of the generator. This will be the focus of this research, which will be further explained in this paper.

II. SYSTEM DESCRIPTION

Fig. 1 gives an overview of a grid-connected wind turbine system. The system consists of the turbine blades (a), the permanent magnet synchronous generator (PMSG) (b), the rectifier (c), the inverter (d) and the distribution grid (e).

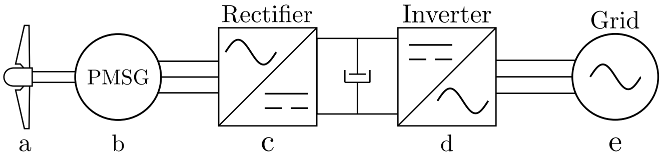

Fig. 1. Overview of a wind turbine system

Since the generator produces ac voltages and currents with a variable frequency and amplitude, called ‘wild ac’, they must be rectified by the rectifier. Most commercial wind turbine systems use a passive diode rectifier combined with a boost chopper, which is shown in Fig. 2.

The passive diode rectifier offers a low-cost solution to convert the three-phase ac currents to a dc current. The boost chopper converts the variable voltage of the rectifier output to a constant voltage V_{dc} at the inverter input. The control

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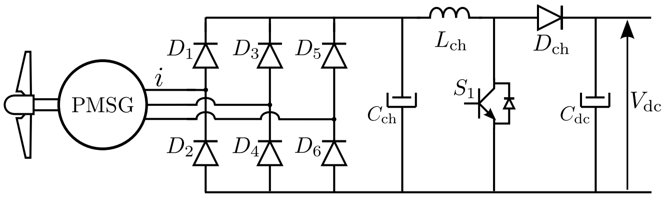
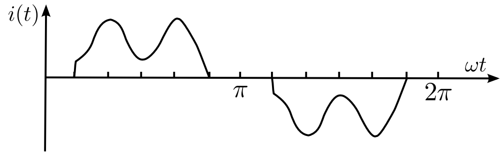


Fig. 2. Passive diode rectifier and boost chopper

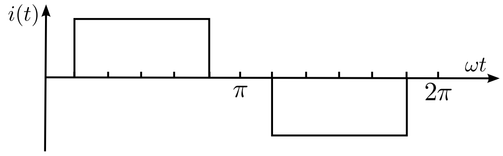
algorithm of this boost chopper is capable of controlling the shaft speed of the turbine. A Maximum Power Point Tracking (MPPT) algorithm determines the desired shaft speed for each wind speed such that the aerodynamic efficiency or power coefficient of the turbine is maximised [6].

III. CURRENT WAVEFORM

The usage of a passive diode rectifier has an important consequence for the efficiency of the generator, since it determines the current waveform in the generator terminals. This current waveform strongly depends on the choice of the component values and circuit topology. Fig. 3 schematically shows two extreme possibilities, i.e. the current waveform for a capacitive chopper input and the current waveform for an inductive chopper input.



(a) Capacitive chopper input



(b) Inductive chopper input

Fig. 3. Current waveforms in the generator

The first current waveform (a) is obtained with a dominantly capacitive input of the boost chopper, i.e. a high value for C_{ch}. The goal of this capacitive input is to attenuate voltage ripples. This is the most encountered situation in practice since it is the most natural rectifier topology, e.g., used in most conventional rectifier loads. A reduced amount of ripple in the dc voltage also allows a simple power measurement, which is mostly used in the MPPT algorithm. The second current waveform (b) is obtained with a dominantly inductive input of the boost chopper, i.e. a low value for C_{ch}. The capacitor C_{ch} can indeed be omitted since it is not essential for the operation of the boost chopper or the rectifier. This is however not done in practice. Both waveforms (a) and (b) contain a high amount of harmonics, which causes additional losses in the generator. Also, it introduces additional torque ripples.

The current waveforms of Fig. 3 will now be obtained with a simulation model in Matlab/Simulink, leading to a more accurate and realistic waveform. Electrical elements are simulated with the PLECS library (Piecewise Linear Electrical Circuit Simulator).

The generator is modeled as shown in Fig. 4. The back-emf is modeled as a three-phase sinusoidal voltage source with a line-to-line rms voltage E of 400 V, a stator resistance R_s of 2 Ω and an inductance L_s of 2 mH. The shaft speed is set at 150 rpm, which is consistent with the low rotational speed of a wind turbine. The generator has 10 pole pairs and therefore produces a voltage with a frequency of 25 Hz.

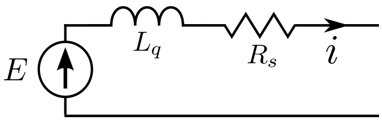


Fig. 4. Model of the generator

The capacitive input voltage V_{dc} of the inverter is modeled as a constant voltage load of 650 V. The inductance L_{ch} of the chopper is set to 15 mH. The active switch S_1 is a PWM-controlled IGBT with a switching frequency of 20 kHz. Fig. 5 shows the control scheme, which is a cascade control loop with a fast inner current controller and a slow outer power controller. The current control loop regulates the current through the boost inductance L_{ch} to a dc set-point with a PI controller. The dc set-point of this current control loop is determined by a slower power controller, emulating the MPPT algorithm. This power controller regulates the mechanical power from the generator to a set-point of 10 kW. The mechanical power is calculated from the back-emf voltages and the currents.

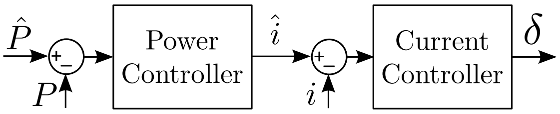


Fig. 5. Control scheme of the boost chopper

The model is used to simulate the current waveform in the generator for four different values of the capacitor C_{ch}, i.e., 1 μF, 10 μF, 100 μF and 1000 μF. As mentioned before, the value of this capacitor has a strong impact on the current waveform. Fig. 6 shows the result of this simulation.

In the first situation, i.e. 1 μF, the capacitance is very small such that a dominantly inductive chopper input can be assumed. The resulting current waveform indeed resembles waveform (b) of Fig. 3. The differences between this simulated waveform and the theoretical waveform of Fig. 3 are the non-infinite changes of the current during the commutation of the diodes, and the presence of a high-frequent ripple. The non-infinite change of current can be expected since inductance is always present in practice. The high-frequent ripple is caused by the switching of the boost chopper and originates naturally in converters with current control loops.

In the second situation, i.e. 10 μF, a low-frequent ripple is present which does not origin from the high-frequent switching of the boost chopper. The waveform clearly starts to deviate from the trapezoidal waveform (b) of Fig. 3. In the third situation, this ripple has increased and starts to resemble

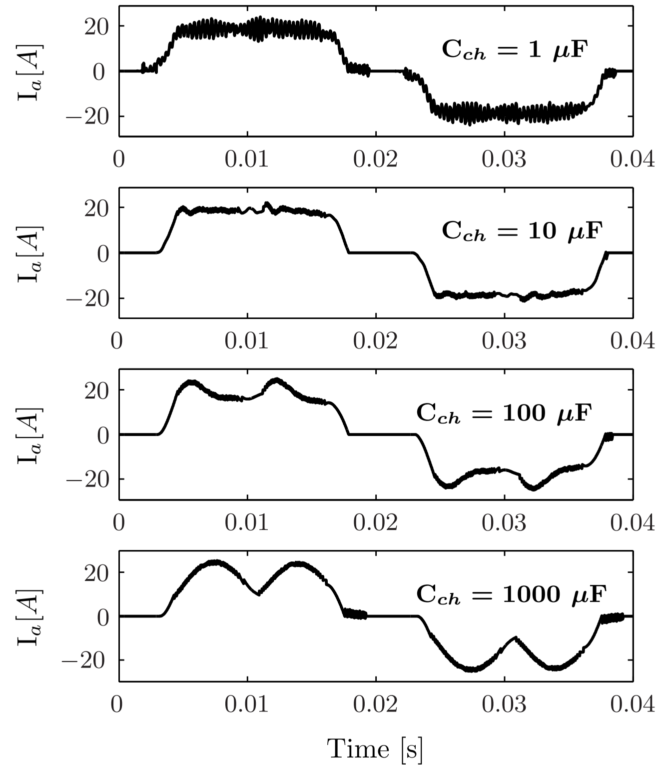


Fig. 6. Simulated current waveforms

waveform (a) of Fig. 3. In the last situation, i.e. 1000 μF, the capacitor is very large and has a nearly constant dc voltage. The boost chopper has a dominantly capacitive input. The resulting current waveform matches waveform (a) of Fig. 3. The high-frequent switching ripple is strongly reduced in this last waveform since the large capacitor C_{ch} acts as a filter.

As mentioned before, the current waveform has an impact on the losses of the generator. In this case, minimal losses would be reached for a sinusoidal waveform. The Joule losses in the stator resistance can be calculated from the power set-point and the back-emf:

$$P_j = \frac{1}{3} R_s \left(\frac{P}{E}\right)^2 = \frac{1}{3}\ 2\ \Omega \left(\frac{10000\ W}{230\ V}\right)^2 = 1260\ W \quad (1)$$

For each of the waveforms in Fig. 6, the Joule losses were calculated from the simulations:

$$\begin{aligned} P_{j,1\mu F} &= 1340\ W & \quad P_{j,100\mu F} &= 1364\ W \\ P_{j,10\mu F} &= 1335\ W & \quad P_{j,1000\mu F} &= 1430\ W \end{aligned} \quad (2)$$

These results confirm that the losses are larger for these non-sinusoidal waveforms when compared to the sinusoidal situation. The fourth waveform of Fig. 6 results in the highest Joule losses and is most encountered in practice in small wind energy systems. This clearly shows the room for improvement.

IV. IMPROVEMENT OF THE WAVEFORM

To increase the efficiency of the generator, the current waveform should be improved. In this section, several possibilities will be given and discussed.

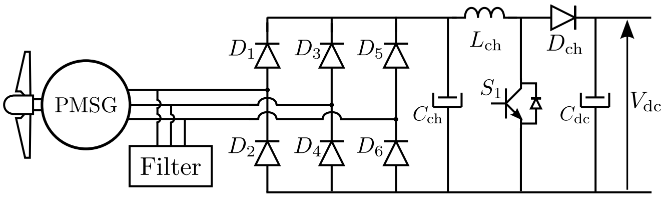


Fig. 7. Passive or active filter on the generator terminals

A. Passive filter

The current waveform can be improved by application of a passive filter on the generator terminals [7], see Fig. 7. This filter, consisting of purely passive components, can be tuned to result in a sinusoidal current waveform for a given frequency. The frequency of the voltage and current waveforms is however variable due to the variation of the shaft speed. The use of a passive filter is therefore not realistic in a variable-speed turbine system.

B. Active filter

Another approach is the usage of an active filter on the generator terminals [8]. This active filter is a small full-active converter, consisting of six active switches and a dc bus. The non-sinusoidal current waveform on the input of the passive diode rectifier is measured and, from this, the fundamental component and the harmonics are calculated. The converter is then programmed to deliver these harmonic components such that only sinusoidal current is present in the generator windings. This approach is inspired by the field of active power filters, which are used to improve the power quality of the grid [9], [10]. More specifically, it is similar to the harmonic current compensation technique [11], [12]. Although it is an original idea to apply this technique on the generator of a wind turbine system, it is far-fetched and leads to a complex, and thus expensive, system.

C. Active rectifier

A radical change of the rectifier topology could also be worthwile. Instead of a passive diode rectifier, a full-active rectifier can be used [13], [14], as shown in Fig. 8. This rectifier consists of six active switches and a dc bus that is directly shared with the grid-connected inverter.

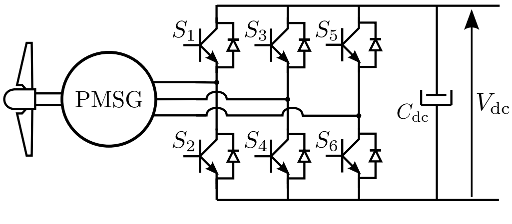


Fig. 8. Active rectifier topology

The advantage of this rectifier topology is the control flexibility. Every desired current waveform can be imposed on the generator terminals. This can result in a considerable efficiency improvement when compared to the current waveforms of the passive diode rectifier in Fig. 6. On the other hand, the active rectifier requires more circuitry resulting in a more complex and expensive converter. Also, the control algorithms are more complex. It should be further investigated whether the efficiency improvement of the generator outweighs the increased cost and complexity of the converter.

D. Goal of this research

The goal of this research is to find a robust solution that ensures an optimal current waveform, independent of the wind speed. The active rectifier is a promising solution but requires further research to be successful. The main attention points are to find the optimal current waveform and to quantify the efficiency increase in the generator. This efficiency increase should outweigh the increased cost of a more advanced converter.

V. CONCLUSIONS

Small wind turbines are a promising new technology to further diversify the renewable energy production. Technological improvements are necessary to reach cost-effectiveness. Although the efficiency of the components can be improved, the interaction between these components plays an important role as well. This research analyses the interaction between the converter and the generator, i.e. the current waveform. The aim of this research is to improve the current waveform in the generator by adaptation of the rectifier circuit topology and control algorithms.

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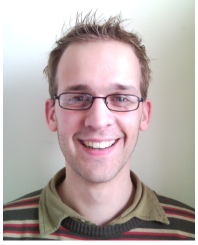

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