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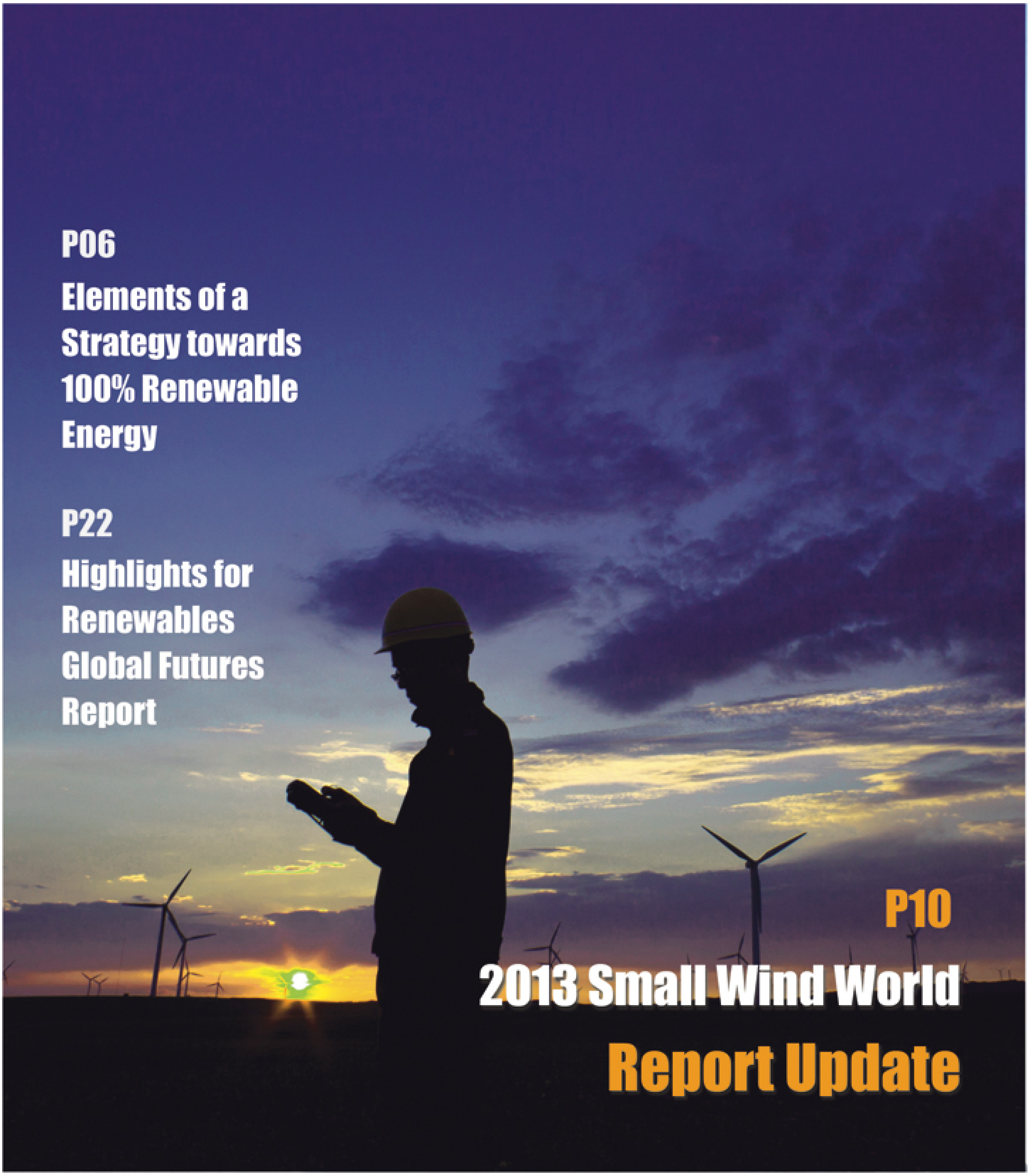

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Contents

The Small Wind Turbine Field Lab Extensive Field Tests for Small Wind Turbines

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Abstract: *This paper describes the research possibilities at the Small Wind Turbine Field Lab and the involved research groups of Ghent University, covering different aspects of a small wind energy system. In contrast to large and medium-sized wind turbines, small wind turbines are still plagued by relatively high production and purchase costs, and low reliability and energy yield. Furthermore, most of them have not been subjected to a field test program. Power-Link, the energy knowledge platform of Ghent University, has for three years operated a modest field test site for small wind turbines, that drew the attention of a lot of manufacturers of small wind turbines. In response, Ghent University decided to launch the Small Wind Turbine Field Lab (SWT Field Lab), to subject small wind turbines to more extensive field tests. Now not only the energy yield is tested, but also topics such as grid integration, structural strength, noise propagation, generator and drive train design and tower construction are studied. All of these parameters are correlated with meteorological data measured on-site.*

1 Introduction

The implementation of small wind turbines in rural and industrial areas allows for a distributed production of renewable energy, considerably reducing the impact on the transmission network. While the benefits are clear, there is still a lot of opposition against small wind turbines. The reasons for this opposition are manifold. Small wind turbines face a variety of legal, economic, spatial, technical and social aspects and constraints (LESTS) that need clarification from an applied research as well as strategic point of view.

As low carbon principles gradually penetrate into business clusters and industrial parks, they unfold new stakeholder dimensions that benefit from a pentadisciplinary assessment, called the LESTS concept [1]. It is noted that small and medium wind turbines meet characteristic technical (T) aspects such as noise generation and grid coupling as well as non-technical aspects such as legal (L), economic (E) and spatial (S) complexity. They moreover suffer from a critical social (S) acceptance.

To tackle these multidisciplinary barriers, Ghent University, together with special interest group Tecnolec, set up the 'Windkracht 13' (Eng: Wind force 13) project within the framework of the Flemish New Industrial Policy, 'Factory of the Future'. By supplying technical advice and recommendations to companies and individuals interested in locally generating power through wind energy and identifying new potential sites for placement, 'Windkracht 13' acts as a leverage for the market introduction of small to medium-sized wind turbines.

Defining the legal context of decentralised energy production [2], balancing the economic gain of concerted actions, rewriting the spatial planning policy in view of clean technological development with industrial, urban and rural impact, as well as promoting social embedding of newtech installations, etc. add to the technical research of the SWT Field Lab. The potential and shortcomings of small to medium turbines in rural areas and off-grid locations is a welcome side-track of the engineering research focus.

To improve the (social) acceptance of small wind turbines numerous requirements must be met. End users expect to buy an appealing turbine with a high benefit-cost ratio, a low cut-in speed, producing no (or only a limited amount of) noise and having a long lifespan. It is up to manufacturers to try to meet these requirements. However most small wind turbines are produced by small companies with limited budgets for research and development. Therefore, many of the small wind turbines currently on the market have a limited field testing(or none at all). In terms of technological maturity, small wind turbines still have a long way to go compared to e.g. big wind turbines or photovoltaic panels. Experience gained from the previous field test program by Power-Link and similar experiments at the Dutch test site Schoondijke [3] show that the technological weaknesses these small wind turbines are currently facing are frequently related to the inverter and grid connection. In addition to this, the

Figure 1 The SWT Field Lab

durability of the drive train components is still uncertain. Last but not least the noise produced by some rotor blades is problematic.

The infrastructure and expertise available at the SWT Field Lab [4] and the involved research groups aims to tackle these challenges. The SWT Field Lab is located in Ostend, Belgium, on the Ghent University Science Park Greenbridge [5].

The emphasis of the SWT Field Lab is on small wind turbines. As a definition, small wind turbines are installations not exceeding a tower height of 15 meters, with an electric power generating capacity limited to 10 kVA. The SWT Field Lab has ten concrete foundations for placement of these small wind turbines. The generator phases of each turbine are individually connected to a measurement board inside a measurement cabin, placed next to the test site. The cabling has been dimensioned in such a way that resistive influence can be neglected. The converters are also placed inside the cabin, and connected to the generator phases. This setup enables easy simultaneous measurements on both the turbine generator and the converter. These measurements are performed by a National Instruments PXI acquisition instrument containing up to one hundred simultaneously sampled measurement inputs. For experimenting with grid integration, the converters can be connected to a fully programmable, four quadrant Spitzenberger & Spies PAS 15000 grid simulator.

Furthermore, a meteorological tower has been placed in the direct environment of the wind turbines. The meteorological tower enables both wind speed and wind direction measurements. The wind speed is measured on five different heights (6, 9, 12, 15 and 18 meters), in order to obtain an overview of its variability in function of the height. Other parameters such as air temperature, air pressure and air moisture are measured to determine the amount of wind energy.

Six of the ten foundations in the Field Lab are reserved for scientific research by Ghent University. The remaining four foundations are available for academic services offered by Ghent University towards companies wanting to test their (prototype) wind turbine, certain components thereof or grid interaction. A motor-generator test bench is available for generator and drive train testing.

The research activities deployed on the Field Lab by Ghent University compromise several subjects, including technical aspects such as the design of the blades, generator, tower and converter, but also non-technical features such as social acceptance or legal aspects of small wind turbine installations.

2 Mechanical Behaviour and Noise

In order to characterise the mechanical behaviour of the mast and/or blades, in-situ monitoring focused on three types of measurements will be performed at the SWT Field Lab: (a) measurements of global motion and vibration, (b) local strain measurements and (c) acoustical measurements.

(a) Global motion and vibration

A first obvious monitoring is the visual inspection. With the help of digital high-speed cameras, the global motion of the mast and/or blades can be followed. There are three digital high-speed cameras available, each with a maximum frame rate of more than 100,000 fps. Till 3000 fps, they have a full resolution of 1024 x 1024 pixels. External trigger signals (e.g. rotation frequency) can be used to capture the images.

Combination with a stroboscope could be considered to better visualize certain motions. This has been done successfully in the past on small vertical axis wind turbines.

A second important parameter is the vibration. This can be measured by accelerometers or a laser vibrometer. The accelerometers measure a local acceleration along a certain axis. The laser vibrometer measures the velocity of the surface point to which the laser beam is pointed.

Different accelerometers can be read out with a transient digital oscilloscope at a rate of 200 kHz for each separate signal. There is channel-to-channel isolation of the grounds, and as such, no cross-talk is possible.

(b) Local strain measurements

For local strain measurements, either classical electrical strain gauges can be used, or optical fibre sensors. Optical fibre sensors are basically the optical counterpart of the electrical strain gauge, but have many advantages: (i) they are not sensitive to electromagnetic interference, (ii) the strain measurements are absolute and no drift appears with long-term measurements, (iii) in case of composites, the optical fibre sensors can even be embedded in the material itself, (iv) several strain measurements can be multiplexed into one single optical fibre cable (like in telecommunication).

The strain gauges (quarter, half or full Wheatstone bridge) can be read out with a maximum sample rate of 50 kHz each, again with channel-to-channel isolation. It has to be taken into account that classical electrical strain gauges are not suited for long-term measurements. If the strains are not small enough, the strain gauges will fatigue themselves, and over time, the signal of the strain gauges will start to drift away (no reference signal anymore).

The optical fibre sensors can be read out at a maximum sample frequency of 10 kHz. Their measurement is absolute, which means that the read-out equipment can be decoupled and coupled on later, without any loss of the reference signal.

In both cases, care has to be taken for temperature fluctuations, so temperature compensation is always necessary.

(c) Acoustical measurements

Sound production by large wind turbines has been extensively studied. In modern large wind turbines, the mechanical noise produced by the generator and gear box has been largely suppressed either by design or by encapsulating the noisiest components, leaving the aerodynamic noise as the most important source of disturbance. Moreover, most large wind turbines use an upwind rotor which reduces the interaction of the blades with the wake of the mast.

For small wind turbines the situation is quite different in many aspects. Firstly it should be mentioned that these small wind turbines generally produce a lower sound power than their bigger counterparts, but at the same time they are placed much closer to the listener and thus may produce high sound pressure levels. Secondly, the balance between efficient – and thus cheap – production and aerodynamically optimal blades often tilts towards higher sound power per energy production balance. Thirdly, small wind turbines operate well inside the atmospheric boundary layer which implies varying and highly turbulent inflow and a matching very specific sound signature.

At the SWT Field Lab, both the sound generation mechanisms and the resulting sound pressure levels can be assessed. For the former, a microphone array (acoustic camera) is available that allows to spatially locate the sound sources and distinguish between aerodynamic interaction between blade and air, generator noise, unstable airstream interacting with the blades, etc. For the latter, long term monitoring of meteorological conditions, energy production, and sound are available. This allows studying the long term average sound exposure, which may for small wind turbines be a more accurate way to assess annoyance and disturbance than maximal sound power used for larger wind turbines.

3 Drive Train

At Ghent University Campus Kortrijk, a test bench has been modified specifically for the validation and characterization testing of the drive train of a small wind turbine with respect to energy efficiency and energy yield. The purpose of the test bench is to determine the energy efficiency of the drive train-consisting of the electric generator (and if required the power electronic converter), the bearing configuration, couplings between the mechanical parts, and the gearbox if present. In its current configuration, the set up allows the testing of turbines with a power rating of 6 kW and rotor blade speeds down to 200 rpm.

A dedicated, highly dynamic electric motor is used to apply mechanical torque to the drive train to be tested. Several torque transducers are available to obtain accurate measurement results (50 Nm, 100 Nm, 200 Nm and 1000 Nm, 0.1% accuracy). The generated electric output of the system is measured by means of a dedicated power analyser. A control system based on a dSpace 1103 controller is used to generate the required torque input. Both steady-state torques and typical wind spectra can be used for testing the drive train. In the latter case measurement data (wind speeds versus time) is gathered on the SWT Field Lab in Ostend or elsewhere.

The first type of tests that can be performed is the determination of the energy efficiency of the individual components of the drive train. The electric generator is most important. The generator can be measured and its iso-efficiency contour map is generated(see figure 2). This contour map shows the efficiency values for different rotor speeds and input torque values. It is based on steady state measurements (fixed speed and torque for each measurement point) and the reproducibility is guaranteed by means of a well described measurement plan including temperature control of the generator and torque transducers. The measurement accuracy of this test is 1%. Generators up to 15 kW can be tested. The use of contour maps allows a good comparison of different generator types and is a powerful tool to select good pieces of equipment when building new generations of small wind turbines. In case the generator is connected to the grid by means of a power electronic converter, the effectiveness of the converter and the implemented generator control scheme (MPPT for example) on the energy yield can also be measured and shown in the contour map.

The second test comprises the entire drive train. Again an iso-efficiency contour map for steady state conditions can be measured by applying fixed input torque and speed. When testing with realistic wind profiles, contour maps can no longer be measured because of the transients involved. In this case the total energy yield for a given wind profile over a predefined window of time is determined. Again, this allows the comparison of different technologies with and without integration of the control scheme and power electronics.

So far the test bench is used for efficiency measurements. In the future, it will also be used for other purposes such as the design of improved MPPT algorithms for small wind turbines, the analysis of vibration and sound levels related to the drive train and condition monitoring techniques.

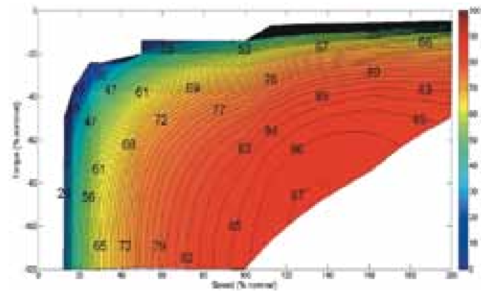

Figure 2 Iso efficiency contour of a 11 kW 1500 rpm IE3 induction generator

Figure 3 Test bench at Ghent University Campus Kortrijk

4 Generator

(a) Generator design

At Ghent University, a lot of research into the design of generators for small wind turbines has already taken place. This research has four goals:

• A first goal is to optimise the geometry to have a maximal annual energy output for a given mass of the generator. The total energy output per year is important because it determines the financial yield of the turbine.

• A second goal is to increase the operating range of wind speeds, to allow operation at lower wind speeds, hence machines with a low cogging torque will be studied.

• A third goal is to build up insights in the thermal design. In small wind turbine applications, the generator is most of the time in a transient working condition, and moreover, it may be exposed to extreme conditions of temperature and humidity. This makes the thermal design a much bigger challenge than for drives in steady state.

• The fourth goal is to implement current research about condition monitoring of Permanent Magnet Synchronous Generators (PMSGs) to one or more turbines in the SWT Field Lab. The condition monitoring can detect among other things excessive temperatures in the magnets or eccentricity problems.

Concerning the generators, the goal is to study three types of direct drive - hence low speed - electrical machines that have inherently good characteristics for application in small wind turbines:

• A radial flux permanent magnet synchronous machine with outer rotor has a higher torque to mass ratio than conventional radial flux machines with inner rotor.

• A dual rotor axial flux permanent magnet synchronous machine with stator core in laminated iron is a machine with very high torque to mass ratio and high efficiency for the low speed and high torque wind application (Figure 4).

• A dual rotor axial flux permanent magnet synchronous machine with ironless stator is often described in literature as the preferred machine for wind energy applications. The absence of iron in the stator completely eliminates cogging torque, so that the self-starting of the turbine at very low wind speed is not hindered. Another benefit is the weight reduction.

Another research topic is the adjustment of generator design for maximising annual energy output, based on the Weibull distribution. The optimisation will be run using the Weibull distribution giving the probability to have – at a given geographical location – a given wind speed during the year. The chosen approach will ensure the best overall operation of the generator over the entire operating range defined by the Weibull distribution. This means that the total energy output per year is optimised. This energy is obtained as the integral of the power distribution function over the entire wind speed range. This in contrast to the state-of-the-art optimisation which takes into account only the nominal working conditions of speed and torque.

The procedure that will be followed is as follows: from the Weibull distribution and from the mechanical efficiency of the turbine blades, a relation can be

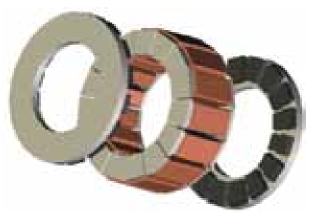

Figure 4 The axial flux PM generator consisting of rotor – stator – rotor [6]

Figure 5 The stator designed and built at Ghent University [6]

established between the mechanical power on the shaft of the generator, and the probability (i.e. the number of hours per year) that this power occurs. In this phase an ideal maximum power point tracking system is assumed (see below). For each wind speed, the electrical power is found as the product of the mechanical power and the efficiency of the conversion at that speed. The total energy output per year can be found by integrating the product of electrical power and wind probability over the total wind speed range.

Additionally, research into the thermal design is done based on Computational Fluid Dynamic simulations. Appropriate cooling techniques can be studied for the three types of machines mentioned. For the thermal design, it is important to know the typical load and speed patterns of the generator. Therefore, a measurement campaign of the wind speed at low height is being done at the SWT Field Lab. The data will be combined with thermal models of the generators in order to study the thermal behaviour.

Finally, condition monitoring will be done by measuring the voltages and currents of the generator, and combining these data with models of the generator. By analysis of the measured data, it is possible to detect local demagnetisation of magnets (e.g. due to too high temperature), or eccentricity because of mechanical overload on the shaft or bearing damage.

5 Power-Electronic Converter

The power-electronic converter converts the raw power from the generator into voltages and currents suitable for injection into the grid. Furthermore, the converter performs the Maximum Power Point Tracking (MPPT) to ensure a maximal power coefficient of the turbine.

In the SWT Field Lab, several aspects of the converter will be investigated, e. g., the performance of the MPPT, the interaction between the converter and the grid and the impact of the converter on the generator efficiency.

The goal of the MPPT is to control the shaft speed of the turbine proportional to the wind speed to maximize the power coefficient. Previous research has shown that there is room for improvement in the performance of these MPPT algorithms [7]. Poor performance of the MPPT results in less capture of renewable energy and thus a reduced energy yield. The SWT Field Lab will be used to experimentally evaluate the performance of the MPPT of the different converters. Due to the modular setup of the lab, the regular converters can be replaced with newly developed experimental converters. Several new MPPT algorithms will be implemented on these converters which will allow us to a comparison of their performance with the standard MPPT algorithm of the original converter. The goal is to improve the yearly energy yield of the turbine.

The interaction of the converter with the power quality of the grid is another aspect which will be investigated. With the PAS 15000 mains simulator, a three-phase distribution grid can be emulated including several power quality issues such as voltage waveform distortion, voltage dips, unbalance or flicker. In a realistic distribution grid, all these power quality issues can occur. Therefore, the converter should be robust enough to survive these issues to a certain extent. In the SWT Field Lab, the operation limits regarding power quality of the converters will be measured and evaluated. This allows the identification of possible shortcomings in current commercial converters, which can then be tackled by focusing our research on these crucial aspects.

Finally, the impact of the converter on the generator efficiency will be investigated. The circuit topology and control strategy of the rectifier stage has a strong influence on the losses in the generator. More specifically, the use of passive diode rectifiers results in a current waveform with a large harmonic content and a low power factor, resulting in high losses in the generator. In the SWT Field Lab, measurements of the current waveforms will be performed to estimate the impact on the generator losses. Possible solutions will be implemented on experimental converters, which will then be deployed in the SWT Field Lab to measure the efficiency improvement in real-life conditions.

6 Conclusion

The SWT Field Lab described in this paper allows for extensive and multidisciplinary research to be done on small wind turbines. The academic service offered by Ghent University provides a direct link to the industry, allowing manufacturers of small wind turbines to take advantage of the research infrastructure and expertise to develop new or improve existing small wind turbines. It is the authors' belief that the SWT Field Lab and the research performed there will close the gap in technological maturity between small wind turbines and other renewable energy technologies such as large wind turbines and photovoltaics, hopefully leading to a higher degree of public acceptance and rate of adoption.

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