Holistic Design of Small-scale Stand-alone Wind Energy Conversion Systems Using Locally Manufactured Small Wind Turbines

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Abstract. A holistic and multi-disciplinary design approach is developed for small-scale stand-alone wind energy conversion systems (WECS) using locally manufactured small wind turbines (LMSWTs), with the aim of reducing capital and maintenance costs while increasing the annual energy production and energy utilization of such systems. Various subsystems are analysed and modelled, using both sequential and integrated design approaches, such as the rotor, including the airfoil and blade geometries, the axial flux permanent magnet generator including economic, thermal and structural aspects of the stator and rotor geometry, the furling system and the electrical system, including the power transmission cables and the battery bank. The holistic design approach is then applied to a 2.4m rotor diameter LMSWT and the complete WECS is dimensioned. Finally, the designed low cost system is compared to a high cost system using a maximum power point converter, with satisfactory results especially for low wind speeds around the mean wind speed of the site. It is thus concluded that a holistic and multi-disciplinary design approach to small-scale stand-alone WECS using LMSWTs, can lower the cost of energy for rural electrification applications by reducing capital costs, while sustaining the system’s efficiency and annual energy production in low wind speed regions.

1. Introduction
The UN Sustainable Development Goals (SDG) cover a range of social and economic issues, with SDG No7 calling for universal access to sustainable and affordable energy by 2030. In this aspect, low cost renewable energy technologies can make small scale electricity production more accessible to rural communities. In particular, the local manufacturing of such technologies can significantly reduce initial costs with the use of locally available materials, tools and manufacturing techniques and at the same time reduce maintenance costs [1] by providing appropriate training to the user community.

A widespread technology with such characteristics is locally manufactured small wind turbines (LMSWTs) [2]-[6] (Fig.1). Available design manuals [7] and on-line tools [8] have been a reference guide for LMSWTs, with many NGOs, technical groups and practitioner networks applying them in the field, in order to locally manufacture small wind turbines for the electrification of rural communities in developing countries. International practitioner networks such as the Wind
Empowerment association are actively promoting the technology of LMSWTs, counting several hundreds of installations on all continents and a growing user community.

LMSWTs are typically part of hybrid stand-alone (off-grid) battery based systems, with installed capacity of renewable energy sources of up to 10kW, while their rotor diameters range from 1.2m to 6m, producing power from 200W to 5kW respectively at 10m/s wind speeds. These small wind turbines are typically variable speed machines which consist of a three blade wooden [9] horizontal axis rotor of constant pitch angle, of a coreless axial flux permanent magnet generator (AFPMG) with a double rotor single stator configuration and utilize a passive gravity furling tail system for rotor speed and power regulation (figure 1).

![Figure 1. Local manufacturing of an AFPMG using simple techniques and an installed 2.4m rotor diameter locally manufactured small wind turbine [3].](image)

The construction of a LMSWT is achieved with simple tools, as encountered in rural workshops for wood and metal working, and with the use of simple manufacturing techniques which do not require skilled labour. Most of the materials used can be sourced locally, while some specialized materials like permanent magnets can be ordered online and delivered by post. Particularly the utilization of an AFPMG, allows for simple manufacturing of the stator and rotor of the generator, with the additional advantage of a simple air gap regulation process which allows for improved turbine and generator power matching abilities [10].

In this paper a holistic and multi-disciplinary design approach [11] is developed for small-scale stand-alone wind energy conversion systems (WECS) using LMSWTs, with the aim of reducing capital and maintenance costs while increasing the annual energy production and the energy utilization of such systems.

2. Methodology

In this paper, a holistic design approach is used in order to achieve a multi-disciplinary design of small-scale stand-alone WECS using LMSWTs for sustainable rural electrification applications. The various multi-disciplinary subsystems of the WECS which are analysed are the rotor (including the subsystems of the airfoil’s shape and the blade’s chord and twist distribution, along with their performance and economic aspects), the AFPMG (including the subsystems of the stator’s and the rotor’s geometry, along with their corresponding performance, economic, thermal and structural aspects [12]), the gravity furling system and the electrical system (including the subsystems of the transmission cables and the battery bank).

2.1. Design requirements for WECS using LMSWTs

A basic objective of this study is to perform a holistic design while analysing and applying the particular characteristics of small-scale stand-alone WECS using LMSWTs, as translated into specific
design requirements. Such design approaches are developed in the following sections for the various WECS subsystems mentioned earlier.

2.1.1. Small-scale stand-alone WECS: Design for low wind speed regions, with mean wind speeds between 4 to 6 m/s, as these are the most frequently encountered mean wind speeds in rural areas and at common hub heights of 12 to 24 meters. Additionally, design for cut-in and rated wind speeds with probabilities of occurrence of above 3.5% for low mean wind speed sites. These lead to the design requirements of maximizing the WECS’s system efficiency at 5 m/s, and using the wind speeds of 3m/s and 10 m/s as cut-in and rated wind speeds respectively.

2.1.2. Rotor (Airfoil): Design for low Reynolds numbers, as they would occur from the cut-in wind speed of 3m/s to the rated wind speed of 10 m/s, for SWTs with rotor diameters from 1.2 to 6m. This leads to the design requirement of maximizing the airfoil’s Lift/Drag ratio at Reynolds numbers between 1x10^5 and 4x10^5 depending on the rotor diameter.

2.1.3. Rotor (Airfoil): Design for local manufacturing, with construction processes which can be achieved with simple tools and manufacturing techniques that do not require specialized labour or machines. This leads to the design requirement of a flat pressure side for airfoils used in LMSWTs.

2.1.4. Rotor (Airfoil): Design for a range of angles of attack (AoA) occurring when the turbine operates in the cut-in to rated wind speeds range, for constant pitch angle blades as used in LMSWTs and for relatively fixed rotational speeds of the rotor due to direct battery charging. This leads to the design requirement of maximizing Lift/Drag within the range of AoA from 1 to 9 degrees, and particularly for AoA that occur in the low wind speed region close to 5 m/s.

2.1.5. Rotor (Blade): Design for a range of wind speeds, as they occur from cut-in to rated wind speed in low mean wind speed sites, and so for a range of tip speed ratios around the optimal. As the capital costs of maximum power point tracking (MPPT) converters frequently exceed the financial resources of rural electrification applications, the rotational speeds of the rotor are relatively fixed due a direct battery connection, which then lead to the operation of the rotor over a range tip speed ratios and of AoAs. This leads to the design requirement of designing rotors from 3 and 10 m/s, for a 5m/s mean wind speed site, and for tip speed ratios from 5 to 7, with an optimal tip speed ratio of 6.

2.1.6. AFPMG: Design for a low cost and low mass generator, as this is the most costly component of a LMSWT, and thus could challenge the limited financial resources of a rural electrification project, and additionally the heaviest component of a LMSWT, which could hinder, both in terms of cost and labour, the installation and tilt-up of the tower in remote locations. Also, design for maximizing the efficiency of the generator in low wind speeds, close to mean wind speeds of 5 m/s, in order to maximize the overall WECS’s efficiency at low wind speed regions. This leads to design requirements on the geometry of the AFPMG’s rotor, which carries costly permanent magnets, and on the number of generator poles, with respect to minimizing cost and mass while maximizing efficiency in low wind speed regions.

2.1.7. Furling system: Design for a low rated wind speed, as this reduces loads on the LMSWT and in turn increases durability and reduces maintenance requirements, yet without reducing significantly the annual energy production of the LMSWT, if operating in low mean wind speed regions, between 4 to 6 m/s. This leads to design requirements on the geometry of the LMSWT’s gravity furling system, which is consist of various angles and offsets, with the design requirement of reaching rated power at 10 m/s.

2.1.8. Electrical system (Transmission cable): Design for a specific transmission cable resistance (and a specific AFPMG airgap regulation), which reduces the transmission cable’s cost and also increases the, otherwise relatively fixed, rotational speed of the rotor, in order to achieve higher rotor efficiency,
and thus improved power matching with the AFPMG, by using the voltage drop created on the resistance of the transmission cable and the internal resistance of the AFPMG. This leads to the design requirement of regulating the transmission cable resistance and the AFPMG airgap, by minimizing the WECS’s total cost while maximizing its annual energy production.

2.1.9. Electrical system (Battery SOC): Design for a low battery state-of-charge (SOC), as this is usually the battery bank state during low wind speeds, when electrical energy is most valuable to the WECS. On the contrary, during high wind speeds, the battery bank reaches high values of SOC quickly, due the high availability of electrical energy and due to the battery bank’s limited size. Small-scale battery bank sizes are typical in rural electrification applications due to limited financial resources, and also for better battery life management due to limited power sources. During high wind speeds, the large amounts of energy produced are dumped [13], unless used by the user under an opportunistic energy harvesting approach. This leads again to the design requirement of maximizing the WECS’s system efficiency at wind speeds close to the mean wind speed of the site, usually around 5 m/s, and also designing for a low SOC battery bank voltage.

2.2. Holistic and multi-disciplinary design approach

In this paper a mix of sequential and integrated design approaches [14] are used in order to achieve a holistic and multi-disciplinary design for small-scale stand-alone WECS using LMSWTs. Specifically, when integrated design approaches are used, these are developed using multi-disciplinary design, analysis and optimization (MDAO) techniques and specifically the OpenMDAO framework [15]. The holistic design follows a multi-disciplinary process, which includes all parts of a WECS as mentioned in previous sections, using primarily a sequential design through which the rotor is designed first, then the AFPMG and the gravity furling system and finally components of the electrical system. An integrated design approach is used for the design of the rotor, during which the airfoil and blade geometries are developed concurrently, and the also for the design of the electrical system, where the AFMPG airgap is regulated concurrently with the dimension of the power transmission cable, as shown in figure 2.

![Figure 2. Holistic and multidisciplinary design of small-scale stand-alone WECS with LMSWTs, using both sequential (white blocks) and integrated (blue blocks) design approaches.](image)

In the following sections, the design and optimization processes used in the various multi-disciplinary subsystems of the WECS are presented in detail.

2.2.1. Airfoil design and optimization: An initial airfoil with a flat pressure side is considered, such as the USNPS4 which is frequently used in LMSWTs. The goal of the optimization is to alter the shape of the suction side of the airfoil, in order to achieve a higher Lift/Drag ratio, for the ranges of Reynolds numbers and AoA mentioned in the previous section. The parametrization of the shape of the suction side geometry is achieved through a set of control points which produce sets of Bézier curves, while the polar curves of the various airfoils are computed using the XFOIL code [16]. For the evaluation of the generated airfoil shapes a genetic algorithm (GA) is employed within the OpenMDAO framework. The objective function of the optimization loop is the maximization of the lift to drag coefficient ratio over a predefined range of the operational AoA. The final optimized airfoil design is verified through simulations with the computational fluid dynamics (CFD) in-house code MaPFlow.
2.2.2. Blade planform design and optimization: Design variables of the blade shape optimization loop are the radial distributions of the blade chord and twist for a given airfoil (certain values of the design lift coefficient $C_{l_{des}}$ and the optimum AoA $\alpha_{opt}$). This corresponds to a range of tip speed ratios around the optimal, as mentioned in the previous section. The solution that maximizes the objective function, defines the optimal $C_{l1}$ distribution along the blade span and the optimum inflow angle. Then, different design lift coefficient $C_{l_{des}}$ values obtained at different design AoAs $\alpha_{opt}$ specify input requirements for the airfoil geometry optimization problem. The chord and twist distribution along the radius of the blade are parametrized through a set of control points, which in turn produce sets of Bézier curves for the chord and twist distribution, while their initial positions located within a wide solution space which is based on typical chord and twist distributions for LMSWTs. During this process, the airfoil and blade geometries are evaluated for a three blade rotor using the BEM in-house code RAFT, by producing results of the aerodynamic and thrust coefficients over a range of tip speed ratios and for various wind speeds. The performance of candidate rotor designs is evaluated through a genetic algorithm employed within the OpenMDAO framework, while trying to minimize the objective function (1) of the Levelized Cost of Energy (LCOE) of the rotor and tower, based on the rotor’s Lifetime Energy Production (LEP) and on the rotor and tower lifetime manufacturing and maintenance costs, $RotorLifeCost$ and $TowerLifeCost$ respectively. In addition, the variations in Reynolds numbers are taken into account for different wind speeds and tip speed ratios, depending on the rotor diameter.

$$LCOE = \frac{RotorLifeCost + TowerLifeCost}{LEP}$$ (1)

2.2.3. AFPMG design and optimization: A Particle Swarm Optimization (PSO) algorithm, a common stochastic global optimization method for multi-criteria optimizations in electrical machines, is coupled with a 2D electromagnetic finite element analysis, in order to optimize the AFPMG for cost, mass and efficiency, as described previously. Particularly, the dimensions of a “universal” magnet are optimized, which is a magnet that can be used with good performance criteria in the range of rotor diameters mentioned in previous sections. Four design variables of the AFPMG geometry are optimized, namely the magnet width, length and thickness, along with the stator thickness. The design variables of the optimization can take values from a wide solution space, which was considered to include the optimal solutions after performing some initial trial designs. The number of poles is varied according to the AFPMG power rating for various rotor diameters and the magnet grade is varied from N40 to N45 for Neodymium block magnets, depending again on the AFPMG power rating for various rotor diameters. The objective function $F$ (2) is minimized by reducing the total AFPMG cost $GenCost$ and mass $GenMass$, while increasing the generator efficiency $\eta$. Appropriate penalty functions $P(x)$ are created for candidate designs with stators that overheat or with overweight rotors, while structural aspects of the generator’s rotor are built into the design. Finally, weight coefficients $k_m$, $k_c$, and $k_e$ were introduced in order to able to vary the importance of all three performance criteria in the optimization.

$$F = (1 - \eta) \cdot k_e + GenMass \cdot k_m + GenCost \cdot k_c + P(x)$$ (2)

2.2.4. Furling system design: The gravity furling system is designed based on an iterative process which attempts to converge values for the rotor offset and the vertical angle of the furling tail hinge, based on the thrust coefficient produced in earlier stages of the design process, while using the rated wind speed defined in the previous section.

2.2.5. Electrical system design and optimization: In order to size the system’s transmission cables and also regulate appropriately the AFPMG airgap, the complete WECS is modelled in Simulink and optimized for minimum cost and maximum Annual Energy Production, while optimizing the power matching between the aerodynamic and the electrical components of the system. The rotor, including airfoils and blades, along with the furling system are modelled using NREL’s FAST tool, while the AFPMG and the rest of the electrical system, including transmission cable, rectified and battery bank,
are modelled using appropriate Simulink models, as shown in figure 3. The objective function to be minimized is that of the Levelized Cost of Energy (LCOE) of the complete WECS, based on the system’s energy production throughout its lifetime, over the system’s lifetime manufacturing and maintenance costs.

Figure 3. Simulation of the WECS in the Simulink environment, using Simulink models for the AFPMG, the power transmission cable, the rectifier and the battery bank, in addition to NREL’s FAST Simulink model for the rotor and gravity furling system.
3. Results
In this section the design approaches presented previously are applied to a 2.4m rotor diameter LMSWT as a case study, with the aim of achieving an improved system performance through a holistic and multi-disciplinary design of small-scale stand-alone WECS.

3.1. Airfoil design and optimization: An improved airfoil shape (figure 4) was designed for a LMSWT rotor of 2.4m diameter, by optimizing the shape of the suction side while keeping the pressure side flat, for simple manufacturing. The range of Reynolds numbers for a 2.4m diameter small wind turbine, at a blade radius from 50 to 85% and over a range of wind speeds from 3 to 10m/s, is from \(1.15 \times 10^5\) to \(1.8 \times 10^5\), while in the low wind speed region around 5m/s, Reynolds numbers are in the area of \(1.5 \times 10^5\). Thus, the new airfoil shape was optimized for a Reynolds number of \(1.5 \times 10^5\), and produced improved Lift/Drag ratios for a wide range of the AoA under investigation, and additionally for AoA between 5 to 7 degrees which are encountered in the low wind speed region around 5m/s. In comparison with the frequently used USNPS 4 airfoil, a maximum improvement for the L/D ratio of 16.5% at an AoA of 8 degrees was observed (figure 5). The performance of the optimized and USNPS 4 airfoils over the full range of Reynolds numbers encountered by a 2.4m diameter small wind turbine can be seen in figure 6. It can be observed that the optimized airfoil reaches higher L/D values and for larger ranges of AoA, for all the Reynolds numbers investigated.

![Figure 4](image1.png)

**Figure 4.** An improved airfoil shape for LMSWTs, over the frequently used USNPS 4 airfoil, both with a flat pressure side for simple manufacturing, using a GA and set of Bézier control points.

![Figure 5](image2.png)

**Figure 5.** The Lift/Drag ratio \(L/D\) (left) and the Lift and Drag coefficients \(C_l\) and \(C_d\) (right) over a range of AoA for the optimized and USNPS 4 airfoils, at \(Re 1.5 \times 10^5\).
Figure 6. The Lift/Drag ratio $L/D$ over a range of AoA for the USNPS 4 (left) and optimized (right) airfoils, over the operational range of Re for a 2.4m diameter rotor, i.e. from Re $1 \times 10^5$ to $1.75 \times 10^5$.

3.2. Blade design and optimization: An improved blade geometry (figure 7) was designed for a LMSWT rotor of 2.4m diameter, operating at a Reynolds number of $1.5 \times 10^5$, by optimizing the shape of the chord and twist distribution, while keeping the relative thickness constant at 12%. The chord and twist were kept constant close to the root, specifically up to 15% of the blade radius, for simple manufacturing. The new blade geometry produced 14.5% more power than typical geometries used for LMSWT blades, over a wide range of wind speeds under investigation (figure 8). It can be observed that the optimizer qualifies rotor geometries with reduced chord lengths in order to reduce material costs, particularly towards the root which contributes less in power production.

Figure 7. The chord (left) and the twist (right) distribution over the non-dimensionalized blade radius, for optimized and typical LMSWT blade geometries.

Figure 8. The mechanical power produced by the rotor of the optimized blade geometry over a typical LMSWT blade geometry.
3.3. **AFPMG design and optimization:** The dimensions of a “universal” magnet were designed, with the aim of providing good performance criteria over a range of rotor diameters close to the 2.4m rotor diameter designed in the previous sections, namely from diameters of 2.4 to 4.2m. “Universal” magnets are a cost effective solution for the local manufacturing of AFPMGs, as usually small quantities of magnets are purchased. A Neodymium NdFeB magnet of grade N40 and dimensions for LxWxT of 49x39x10mm was designed using the PSO algorithm, and optimized for producing AFPMGs with minimum cost and mass, and maximum efficiency (table 1), with an overall improvement in performance of 8% when compared to typical magnet dimension used in LMSWTs.

| Rotor Diameter (m) | Efficiency (%) | Cost (EUR) | Mass (kg) |
|-------------------|----------------|-----------|-----------|
| 2.4               | 91             | 347       | 12        |
| 3                 | 89             | 408       | 21        |
| 3.6               | 90             | 527       | 28        |
| 4.2               | 87             | 628       | 44        |

**Table 1. Performance of AFPMGs using a “universal” magnet design**

3.3.1. **Furling system design:** Using the thrust coefficient of the optimized rotor (figure 9), a gravity furling system is designed in order to begin limiting the output power of the rotor at the rated wind speed of 10m/s. Values for the gravity furling design parameters, namely the rotor’s shaft axis offset to the tower and of the vertical angle of the tail hinge, are produced over an iterative process.

![Figure 9](image.png)

**Figure 9.** The thrust coefficient of the optimized rotor (left) and the basic design parameters of the gravity furling system (right).

3.4. **Electrical system design and optimization:** The WECS’s power transmission cables from the LMSWT to the direct connection of the battery bank, were dimensioned while optimizing the complete WECS’s LCOE. During the same process, a power matching between the aerodynamic and the electrical components of the system was performed, which apart from determining the system’s required electrical resistance, also determines the optimal airgap regulation for the AFPMG, in order to maximize the system’s energy production, over a life time of 20 years. For the case of the 2.4m rotor diameter LMSWT, an airgap of 6mm maximizes the AEP over all distances of the wind turbine to the battery bank (figure 10, left), while the appropriate power transmission cable dimensions depend on the distance of the wind turbine to the battery bank, and vary from 2.5 to 4 mm$^2$ for a 6 mm airgap (figure 10, right). All the WECS’s configurations in the left graph of figure 10, represent minimum LCOE configurations for each point.
Figure 10. The WECS’s annual energy production is maximized for the choice of a specific AFPMG airgap (left), while using a specific power transmission cable resistance for connecting to the battery bank (right).

Finally, the holistically designed WECS’s efficiency is compared with a WECS using a maximum power point converter (MPPT), which represents a highly efficient yet expensive setup, as its cost may be comparable to the cost of a complete LMSWT with a 2.4m rotor diameter. As shown in figure 11, the power curves of the two systems are closely matched for wind speeds in the low wind speed region of 5 to 6m/s, which has been the main design goal of this approach. Similarly, the low cost setup of a holistically designed WECS without a MPPT, operates at comparable efficiencies in the low wind speed region with a costly setup using a MPPT, as shown in figure 12. Specifically, the low cost set up stays within a 10% difference in efficiency when compared to the setup using a MPPT, for wind speeds from 5 m/s up to 9 m/s (figure 13), which cover most to the wind speed range of power production of a small-scale stand-alone WECS, which ranges from 3 to 10 m/s. In terms of the AEP, the holistically designed WECS produces 1253 kWh/year, while the system using a MPPT produces 1485 kWh/year, i.e. a 18.5% increase in AEP. Yet, this increased energy production occurs in the high wind speed region, i.e. for wind speeds above 9m/s, during which the battery bank of a typical WECS will reach full charge in a short period of time [13], and the extra energy will be diverted to a dump load and wasted, unless a productive use for this energy has been designed into the system.

Figure 11. The holistically designed WECS’s power curve is comparable in the low wind speed region with a system using a Maximum Power Point Tracking converter.
Figure 12. The holistically designed WECS’s efficiency is comparable in the low wind speed region with a system using a Maximum Power Point Tracking converter.

Figure 13. The holistically designed WECS’s efficiency stays within a 10% difference with a system using a Maximum Power Point Tracking converter in the low wind speed region.

4. Conclusion
In this paper, a holistic and multi-disciplinary design approach is developed for small-scale stand-alone WECS using LMSWTs, with the aim of reducing capital and maintenance costs while increasing the annual energy production and energy utilization of such systems. The various WECS’s subsystems such as the rotor airfoil and blade geometry, the AFPMG rotor and stator and the electrical system’s power transmission cables and AFPMG airgap regulation, are analysed and modelled while using both sequential and integrated design approaches. The holistic design approach is then applied to a 2.4m rotor diameter LMSWT and the complete WECS is dimensioned. The optimized airfoil and blade geometries produce an improved power production performance of 14.5% over standard airfoils and blade geometries typically used in LMSWTs. Additionally, a “universal” Neodymium magnet design is optimized for producing AFPMGs with minimum cost and mass, and maximum efficiency, with an overall improvement in performance of 8% when compared to typical magnet dimension used in
LMSWTs. Additionally, a gravity furling system is designed in order to begin limiting the output power of the rotor at the rated wind speed of 10m/s. Finally, a power matching between the aerodynamic and the electrical components of the system is performed for determining the electrical system’s required resistance and the optimal airgap regulation for the AFPMG, for minimizing the WECS’s LCOE. As a conclusion, the holistically designed low cost WECS is compared to a system of higher cost which uses a maximum power point converter, and it is found to stay within a 10% difference in efficiency when compared to the system with the MPPT, for wind speeds from 5 m/s up to 9 m/s. It is thus concluded that a holistic and multi-disciplinary design approach to small-scale stand-alone WECS using LMSWTs, can lower the cost of energy for rural electrification applications.

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