Open Design and Local Manufacturing of Small Wind Turbines: Case Studies in Ethiopia and Nepal

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Abstract — **During the last decade, the local manufacturing of small wind turbines is becoming an increasingly common approach in rural electrification applications, especially among international networks of renewable energy practitioners. As the number of locally manufactured small wind turbine installations is increasing on all continents, supply chain issues, material shortages or design issues in custom applications are becoming evident. In this paper the development of a series of open access design and analysis tools is presented, which allows the local manufacturer to redesign the small wind turbine according to available materials. In the two case studies, the design tools are used in the field by practitioners in order to overcome supply chain issues during the implementation and design phases of rural electrification projects in Ethiopia and Nepal.**

Keywords—**Wind energy generation, Permanent magnet machines, Ferrites, Neodymium, Battery management systems, Finite element analysis, Manufacturing processes**

I. INTRODUCTION

Low cost renewable energy technologies can make small scale electricity production more accessible to rural communities. 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 by providing appropriate training to the user community. A widespread technology with such characteristics is locally manufactured small wind turbines [1]-[5]. Available design manuals [6] have been a reference guide for locally manufactured small wind turbines, 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.

Locally manufactured small wind turbines (LMSWT) are typically part of hybrid off-grid 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 [7] horizontal axis rotor of constant pitch angle, of a coreless axial flux permanent magnet (AFPM) generator with a double rotor single stator configuration and utilize a passive gravity furling tail system for rotor speed regulation. The use of AFPM generators is typical for these small scale wind energy applications [8]-[10], mostly due to the simple manufacturing techniques required for constructing the stator and the rotor of the machine. Additional advantages are a simple air gap regulation process and the lower cost of materials by comparison with radial flux machines [11]. For the creation of a simple supply chain, commercial off-the-shelf parts from other industries, such as the automobile industry, are also used in the manufacturing, for example the use of a car wheel hub on which the blades and the generator rotors are mounted.

The use of LMSWT is becoming widespread as the technology is actively promoted by international practitioner networks such as the Wind Empowerment association. As the global community is growing and more wind turbines are manufactured and installed, supply chain issues, material shortages or design issues in custom applications are becoming evident. Most local manufacturers use standard designs from reference manuals [6] with a specific bill-of-materials (BOM) and although they are usually easy to source, these materials are not always available in the local markets, or are available after long delivery periods or at a higher than usual prices due to customs taxes. This can pose a problem to the local manufacturers, which can be solved though with the redesign of the wind turbine, and usually that of the AFPM generator, in order to use materials that are available locally at the time. Some typical examples of such cases are the following:

1) *Magnet size and grade:* The magnet size or magnet grade specified in the BOM is not available in the national market and the manufacturer needs to import the magnet at a high cost due to customs taxes and shipping costs. If the local manufacturer does not produce wind turbines in large batches, which is usually the case, then the upfront cost of ordering the magnets from a manufacturer might be prohibitory. The redesign of the AFPM generator for the same power output and for the magnet dimensions that are available locally would provide a more viable solution.

2) *Magnetic material:* The magnetic material specified in the reference design and BOM might not be suitable for the local environmental conditions, as one of the main maintenance issues identified for LMSWTs, has been corrosion of Neodymium magnets in coastal environments [12]. An alternative to Neodymium would be the use Ferrite magnetic materials, yet few designs using Ferrite magnets exist for LMSWTs, so a redesign of the AFPM generator for

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the new magnetic material would be required and this would provide a viable solution to potential corrosion issues.

3) Copper conductor size: The copper conductor size required for the stator wingdings in the BOM might not be available in the local market, and this can be a common issue in developing countries, where a wide selection of material sizes is not always available. The manufacturer again needs to import the required copper wire size, with the same obstacles as explained previously for magnets. A redesign of the AFPM generator for a locally available copper conductor size would again provide a viable solution.

4) Custom applications: The local manufacturer needs a custom AFPM generator design for a specific wind electric application, such as wind pumping or grid connection, or some other electricity producing application such as hydro power or electricity production from biogas. In these cases a redesign of the AFPM generator would again provide a viable solution.

II. OPEN TOOLS FOR SMALL WIND TURBINE DESIGN AND DATA ANALYSIS

After identifying the above mentioned issues, the Rural Electrification Research Group (RurERG) of the NTUA has responded to the needs of designers and practitioners with the creation of a series of open access design and analysis tools. These allow the local manufacturer of a SWT to redesign the AFPM generator according to available materials and for custom applications, while also providing data analysis and optimization tools.

In the case studies presented in the later sections of this paper, the design tools developed by the RurERG have been used in order to overcome specific supply chain issues during the implementation and design phases of rural electrification projects.

A. The OpenAFPM design tools

The OpenAFPM modeling tools can be used for designing AFPM generators for wind electric systems with the use of the open source finite element analysis software 'Finite Element Method Magnetics' (FEMM). The OpenAFPM tools series consists of three design tools named MagnAFPM, UserAFPM and OptiAFPM.

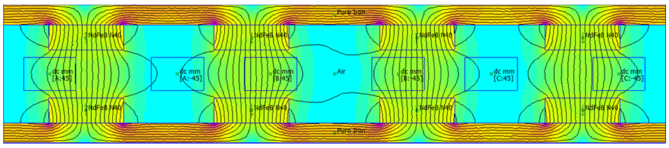


Fig. 1. A 2D finite element analysis in FEMM

The MagnAFPM tool can be used for designing a generator for a specific set of rotor blades and a specific set of permanent magnet dimensions. The UserAFPM tool can be used to validate the performance of a specific generator geometry by performing a 2D finite element analysis using FEMM (Fig.1). The OptiAFPM tool uses the particle swarm optimization (PSO) [13] to optimize the dimensions of the permanent magnets used in the generator design for a specific set of rotor blades, while optimizing the generator's efficiency, cost and/or mass. The OpenAFPM tools have been used for several generator designs constructed in the NTUA, which have been tested for their accuracy with errors of less than 5% [14].

B. The WindSYS design tool

The WindSYS design tool is a modelling tool for wind electric systems with direct battery coupling, which configures the system for maximum annual energy production by optimizing the power transmission cable's cross-sectional area as well as the AFPM generator's air gap, while taking into account the distance between the wind turbine and the battery bank as well as the cable cost. The tool combines the above functions in 3D graphs of annual energy production against AFPM generator air gap and distance from the battery bank, enabling a complete system overview for the optimum power matching of the electrical and the mechanical parts of the wind electric system (Fig.2).

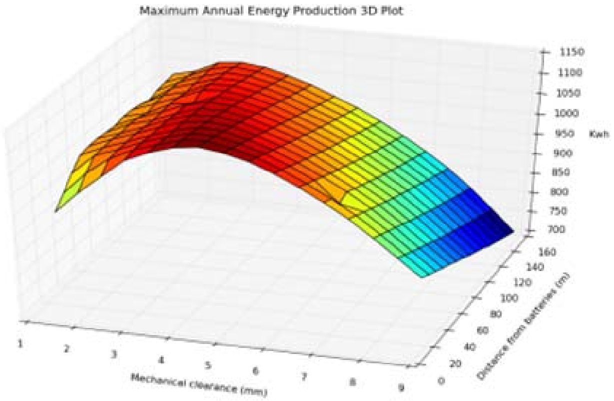


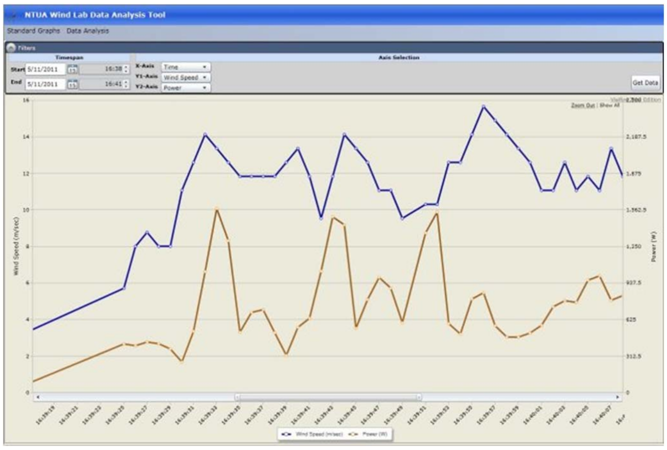
Fig. 2. Annual energy production for variations in the air gap and the power transmission cable length and size

C. The WindLabDAT data analysis tool

The WindLabDAT data analysis tool calculates the performance characteristics of a small wind turbine based on electrical and meteorological measurements, according to IEC 61400-12-1. Standard graphs such as the power curve, the power coefficient and the annual energy production are calculated and presented while data can be displayed in per second raw values or per minute averages (Fig.3). All data can be plotted for different combinations of variables and custom made queries can be made to the data base with regard to all data variables. As several local manufactures perform monitoring of their wind turbine installations using low cost data loggers and sensors, this tool provides an easy way of visualizing and analyzing data, according to IEC international standards.

III. SMALL WIND TURBINE DESIGN FOR LOCAL MANUFACTURING

When designing an AFPM generator for a specific blade rotor size, the OptiAFPM tool can used in order to optimize the magnet dimensions (length, width and thickness of rectangular magnets) for different weighted performance criteria such as efficiency, cost and/or mass. Then the MagnAFPM tool can be used to perform the preliminary design of the AFPM generator using the optimized magnet dimensions. Finally, the UserAFPM tool can be used to perform a 2D finite element analysis (FEA) simulation with FEMM, to check the efficiency, the rated power and the overall performance of the design in more detail. Then the new AFPM design is simulated for direct battery connection with the WindSYS tool, in order to provide the user with information on how to install the wind turbine, i.e. how to regulate the air gap and what size of power transmission cable to use, in order to maximize the annual energy production of the system. Finally, if the wind electric system is installed and monitored, the WindLabDAT tool can be used for the analysis of the electrical and meteorological sensor data.



Start 5/11/2011 16:38
End 5/11/2011 16:41
X-Axis Time
Y1-Axis Wind Speed
Y2-Axis Power

Fig. 3. Observing the furling system behavior with per second values for wind speed and power production

In the following sections, the design principles used in the tools are presented in order to provide more insight into the process. A more detailed analysis of the design process can be found in [15]-[17].

A. Nominal wind speed

The cut-in wind speed of a LMSWT is typically at around 3m/s, but a stronger wind gust of about 4.5m/s will be required to start the blade rotor from stand still. If the air gap of the AFPM generator is increased then this will also increase the cut-in RPM and cut-in wind speed of the wind turbine. On the other hand, this can be used, to an extent, to regulate the power matching of the blades to the generator [18] and bring the blade rotor out of stall and more towards its design tip speed ratio. Choosing the correct cable size for connecting the wind turbine to the batteries will help more in this direction though. The nominal wind speed is usually chosen to be around 10m/s and this value corresponds to a high but frequent wind speed for which the generator will be designed to produce its rated power. Higher nominal wind speeds can be chosen but they will occur less frequently, so this is not a usual design approach, yet this will depend on the mean wind speed of the location. A more common design approach is to choose a lower nominal wind speed, when a large rotor is mounted on a small generator, in order to produce more power at lower wind speeds, which is good for low mean wind speed sites. In either case, when choosing a higher or lower nominal wind speed than 10m/s during a design, the nominal aerodynamic coefficient of the blades needs to be chosen accordingly in relation to the nominal tip speed ratio.

B. Tip speed ratio and aerodynamic coefficient

When directly connected to batteries the blade rotor will stall at a tip speed ratio (TSR) of about 4.5 at 10m/s and will operate with an aerodynamic coefficient of about 0.3 (Fig.4). When connected through a maximum power point (MPP) converter the blade rotor will operate close to the optimal TSR (design TSR of the blades) and will operate with an aerodynamic coefficient of about 0.38 [19], and this will occur for a wide range wind speeds. The nominal TSR will be determined by the RPM of the generator at the nominal wind speed which is proportional to nominal voltage of the AFPM synchronous generator, which in turn will depend on the battery voltage and the losses on the transmission cable between the wind turbine and the battery bank. The nominal TSR will also define the nominal value of the nominal aerodynamic coefficient and this in turn will define the nominal current at nominal power production. The diameter of the copper wire in the coils will be determined by the nominal current so the choice of a realistic TSR and aerodynamic coefficient for the nominal wind speed during the design phase is important in order to operate at rated current with a reasonable efficiency.

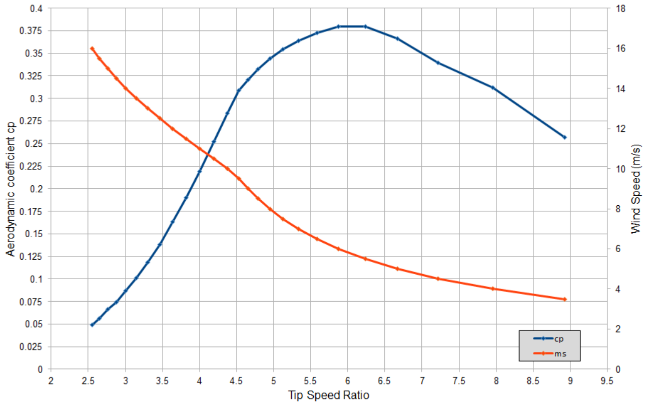


Fig. 4. The aerodynamic coefficient of the blades and the wind speed against tip speed ratio for direct battery coupling

C. Rotor disk thickness

The rotor disk thickness is calculated by the design tools and the result corresponds to the minimum disk thickness which will not produce saturation of the steel disk. This calculation though does not take into account the deflection of the rotor disks due to the attractive forces between the magnets in a double rotor topology, as this requires further structural finite element analysis [20]. So when constructing the generator, and especially for large outer diameters and strong magnets, a few millimeters need to be added to the disk thickness in order to produce minimal deflection of the disks at the outer radius. The tradeoff for doing this is increasing the magnet rotor disk weight, which can be substantial for large wind turbines, so a balance needs to be found between the two. For larger AFPM machines introducing holes in the rotor disks can help in reducing their weight.

D. Magnet grade

Several grades of Neodymium magnets can be used in the design tools and the higher the grade of the magnet the more flux density in the air gap. In addition, a smaller air gap provides less resistance in the magnetic loop, which means more flux density in the air gap to induce voltages in the coils. So while trying to reduce the air gap between the rotors in order to use as much of the potential of the magnetic material as possible, there also needs to be enough space in the air gap to accommodate for the stator thickness and also for a good mechanical clearance between the rotating and stationary parts of the generator, i.e. the magnet rotors and the stator coils. Typical mechanical clearances of 3 or 4mm can be used on either side of the stator, in order to accommodate for maintenance issues that might build up gradually over the years, such as loose bearings in the hub, the stator warping due to heat losses and the Neodymium magnets swelling from corrosion. Both the thickness of the stator and the mechanical clearance, increase the axial spacing of the magnet rotors so they reduce the flux density in the air gap. The necessity for large air gaps is one of the disadvantages of axial flux machines over the very small air gaps of their radial flux counterparts. For this reason, large amounts of magnetic material are required in axial flux machines, i.e. large magnets, in order to produce the required flux density in the air gap. If the goal of a design is to increase the mechanical clearance of a generator while keeping the flux density in the air gap the same, then increasing the magnet grade is a possible solution.

E. Magnet thickness

Increasing the thickness of the magnets allows for a larger air gap between their opposing faces for keeping the same amount of flux density in the middle of the air gap, i.e. in the middle of the stator for a double rotor topology. When the thickness of the stator needs to be increased in order to accommodate more copper for a given generator diameter, then increasing the magnet thickness will provide significantly more millimeters in the air gap than other measures, such as increasing the magnet grade for example. When altering the magnet thickness in order to increase the stator thickness, the new stator thickness can be calculated by using the design tools.

F. Number of poles

By increasing or reducing the number of poles, magnets are spaced closer and further way from each other for a given rotor diameter. A measure for this is the magnet width-to-pole pitch ratio (ai) which essentially describes how close to each other the magnets are placed on the disk, with values ranging from 0 to 1. By increasing the number of poles while designing the generator for a given blade rotor, the efficiency of the generator is increased as more magnets and less copper are used to produce the same power. There is a limit though to how much the efficiency can increase because as the magnets move closer together the flux leakage increases, so essentially flux is lost from the air gap and this counteracts the effect of introducing more magnetic material. In practice the efficiency will not increase significantly for values of ai above 0.6 for Neodymium magnets, which is when the distance between two adjacent magnets is about the same as their width. On the other hand reducing the number of poles will reduce the generator's efficiency but will also reduce its cost as less magnets are used. A balance between efficiency and cost can be found in designs with ai ranging from 0.4 to 0.5 for Neodymium magnets [21]. In terms of size an increase in the number of poles will reduce the volume, mass and diameter of the generator. In generators using Ferrite magnets, which have lower flux densities that Neodymium magnets, a higher number of poles is necessary to produce the same power from a given rotor. So Ferrite magnet machines would find their balance of efficiency and cost in designs with ai ranging from 0.6 to 0.7, as Ferrite magnets are cheaper and need to be used in larger volumes.

G. Heat coefficient

The heat coefficient describes how much thermal energy the coils can dissipate from their surface area. A high value of the heat coefficient means trying to transfer large amounts of thermal energy through a small surface area, which will end up heating the stator fast at high temperatures. This will risk over-heating the stator if other measures are not taken, such as regulating the furling system to operate at lower wind speeds than the nominal. In order to avoid temperatures of more than 115 degrees Celsius in the stator, which will gradually degrade the enamel insulation of the copper wires, the heat coefficient should not exceed the value of 0.4W/cm^2. Choosing low values of the heat coefficient will result in designs with higher efficiency and lower temperatures in the stator, but with larger generator diameter and heavier parts.

H. Current density

The current density will define the amount of thermal losses in the stator and in turn the efficiency of the generator, as thermal losses are significantly higher than rotational losses and eddy current losses. This means that high values of current density will produce less efficient generators at the nominal wind speed. Yet for direct battery connection this is not a problem, as due to the low nominal TSR, the blades will stall and the efficiency of the blade rotor will be significantly reduced at the nominal wind speed. On the other hand there is more energy to be harnessed in wind speeds closer to the mean wind speed of the site and it is then that an efficient generator is more useful. For systems operating with a MPP converter, such as grid-tied wind turbines, more efficient generators at the nominal wind speed can actually be useful, as the blades will be operating at higher efficiencies and close to their design TSR. A more efficient generator can be designed by increasing the number of poles and/or by reducing the current density. For AFPM generators for wind turbines without any casing, such as LMSWTs, the current density can take values up to 6.5A/mm^2. Higher values will reduce the efficiency of the generator further and, depending on the value of the heat coefficient, will risk over-heating the stator.

IV. CASE STUDIES

In the following case studies examples of how the design tools have been applied in the field by practitioners in specific projects are presented.

A. Electrification of rural community shops in the Somali and Afar regions of Ethiopia

During 2015, the RurERG joined other Wind Empowerment members and Mercy Corps Ethiopia, in order to provide productive uses of energy from off-grid renewable energy systems using locally manufactured small wind turbines in PV/Wind hybrid systems, as part of Mercy Corps' program PRIME (Pastoralists' Areas Resilience Improvement through Market Expansion) sponsored by USAID.

Fig. 5. The rural community of Sudan Camp in the Afar region of Ethiopia

During the materials gathering phase of the project, several supply chain issues were faced in Addis Ababa. The required copper conductor size for the small wind turbines to be manufactured was not available from several suppliers and the magnet rotor steel disks that were ordered were chiselled by hand, so their outer diameters were different from those specified in the BOM. The OpenAFPM tools were used to redesign the wind turbines in order to use one of the available copper conductor sizes and the actual effective length of the steel disks for the magnet rotors. In this case study it was made evident that the design tools allowed the project partners to act fast in order to address unexpected supply issues, which can be frequently encountered in any development project.

Fig. 6. The 3m rotor diameter LMSWT installed at the rural community of Handew in the Somali region of Ethiopia

During the two phases of the project, local shops in the rural settlements of Handew, 15km away from Jijiga, and of Sudan Camp (Fig.5), 50km away from Semara, were electrified using locally manufactured small wind turbines installed at 12m hub height and solar panels, in order to provide electricity for mobile phone charging, lighting and refrigeration of beverages and local produce in the shops. The off-grid electrical system components can be seen in Table II. The small wind turbines used in the installations were manufactured locally at the Jijiga Polytechnic College during a 7 day course with 22 participants in one case and at the Semara University during a 9 day course with 24 participants (Fig.8) in the other. Graduates, students and staff of the college and of the university participated in the courses which included theoretical lectures on small wind turbine technology and its applications and practical workshops on small wind turbine construction. The wind turbines were then installed with the course participants in the rural communities of Handew and Sudan Camp.

B. Electrification of a rural community clinic in the Palpa Region of Nepal

During 2017, the RurERG joined other Wind Empowerment members from Nepal, specifically the organizations Kathmandu Alternative Power and Energy Group (KAPEG) and People, Energy & Environment Development Association (PEEDA) in order to realize the electrification of a local health clinic and the offices of the Village Development Committee (VDC) in Mityal (Fig.7), a rural community 25km away from the town of Rampur in the Palpa Region of Southwest Nepal, using locally manufactured small wind turbines in a hybrid PV/Wind off-grid system. The electrification project was part of a knowledge exchange activity founded by the Wuppertal Institute for Climate, Environment and Energy (WISIONS).

Fig. 7. The rural community of Mityal in the Palpa region of Nepal

During the design phase of the project, several supply chain issues were faced in Kathmandu, but also a very humid environment was encountered in the Palpa region during the preliminary site visits. Specifically, Neodymium magnets were not available in the local market as specified in the original BOM for a 2.4m rotor diameter small wind turbine, and so they would have to be imported at high costs due to customs taxes, while also needing a lead time of more than a month to arrive at customs, thus significantly delaying the project implementation. In addition, the use of Neodymium magnets in a humid environment needed to be avoided, so the decision to use Ferrite magnetic materials was taken. The Ferrite magnets that were available in Kathmandu were sourced and the OpenAFPM tools were used to redesign the AFPM generator of the wind turbine in order to use the magnets that were available. Also, in this case study, the design tools proved to be valuable in order to address unexpected supply issues, which can be common in development projects.

During the project, the local health post of the rural community of Mityal was electrified using a locally manufactured small wind turbine installed at 12m hub height and solar panels, in order to provide electricity for mobile phone charging, lighting and a laptop computer in the VDC offices and refrigeration of vaccines and lighting in the local health post. The off-grid electrical system components can be seen in Table II. The small wind turbine used in the installation was manufactured locally at the Kathmandu University during a 5 day course with 25 participants, including 15 students (graduates and undergraduates) from 3 different educational institutions of the country and 10 participants from different organizations, such as renewable energy companies and NGO's.

TABLE II
THE COMPONENTS OF THE THREE 24VDC OFF-GRID SYSTEMS CLOSE TO JIJIGA AND SEMARA IN ETHIOPIA AND CLOSE TO RAMPUR IN NEPAL

	Rotor Diameter (m)	***Solar Panels (W)***	***Inverter (W)***	***Battery (Ah)***	***Diversion Controller (A)***
Handew	3	300	500	300	60
S.Camp	3.6	600	1000	750	120
Mityal	2.4	600	700	200	60

Fig. 8. Manufacturing a 3.6m LMSWT with students from the university of Semara in the Afar region of Ethiopia

V. CONCLUSIONS

In this paper the open design and local manufacturing of small wind turbines have been showcased as significant aspects of rural electrification in developing countries. Possible supply chain issues in projects using LMSWTs have been highlighted and addressed with the development of open design tools by the RurERG. Several design tools have been presented in this paper and their design approach explained in detail in order to further empower designers and practitioners of wind electric systems. The case studies presented in this paper have shown the practical significance of these design tools to practitioners during the implementation of projects using LMSWTs. In addition, the case studies have showcased the capacity building potential of LMSWTs and the potential impact towards strengthening the local knowledge base that such projects can provide, with the goal of creating local small enterprises operating in the renewable energy sector.

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