Generator Design for Existent Windmills

From Water Pumping to Electricity Generation

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***Abstract*— The purpose of this paper is to describe the design of a direct-drive, permanent magnet synchronous generator to be used in the addition of electrical generation capability to water-pumping windmills. A characterization of the existing turbine structure is given in order to determine the generator's nominal mechanical input parameters. Electric machine topologies currently used in wind energy conversion are discussed and the machine structure is selected for this application. Finally, the initial design is presented and a brief discussion of the remaining work is given.**

Keywords-axial flux; permanent magnet; wind energy conversion

I. INTRODUCTION

Water-pumping windmills have historically been used as the primary means of obtaining water for both domestic and farming (or ranching) uses in rural areas of the United States, where connection to electric power lines was not an option. In modern times, with the help of the Rural Electrification Administration, most farms and rural homes have access to the electrical power grid and so electric water pumps have replaced these windmills in many instances. However, in spite of their neglect, lattice towers with multi-bladed turbines atop them are still a common sight, especially across the western and mid-western regions of the U.S.

The purpose of this project is to investigate the possibility of retrofitting electricity generation capabilities to these disused windmills, whereby using existing structures to help offset the energy requirements of individual farms or homes. It should be noted that while the ultimate goal for this project is to develop an entire energy-capture system, as illustrated in Fig. 1, the focus of this paper is solely on the generator design. At the time of writing this paper, the manner in which electricity is to be pulled from the turbine has not been determined. However, because most existing windmills are situated close to the homestead and utility cables have previously been laid in order to power electric water pumps, the assumption henceforth is that the system is to be grid-connected.

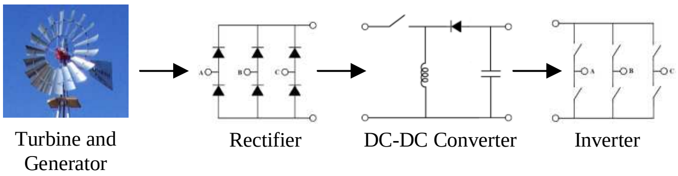

Figure 1. Proposed system for the addition of electricity generation capabilities to water-pumping windmills.

II. TURBINE CHARACTERIZATION

The purpose of this project is to develop an energy-capture system that can be commercially marketed as an "add-on" package by a manufacturer of water-pumping windmills. As such, the capabilities of the electric generator must be appropriately matched to those of the turbine itself. It should be noted that the physical structure of these windmills is optimized for water-pumping, not electricity generation; specifically, they are designed to provide high torques at low rotational speeds. While mechanical redesign of the turbines would surely yield improved electrical power output, this is not an option in the context of this application. Moreover, a typical windmill company offers a variety of turbine sizes; for example, Dempster Industries, LLC offers turbines with rotor diameters ranging between 6 and 18 feet in 2-foot increments. For the initial design iteration, the generator parameters are based on the characteristics of the most popular turbine size (8-ft. diameter), but the final design will be augmented to perform sufficiently with the other rotor sizes.

The maximum mechanical power output of the turbines can be calculated by the standard equation:

$$P_{mech} = \frac{1}{2}\rho A C_p U^3 = C_p P_{wind} \qquad (1)$$

where ρ is the density of air (1.223 kg/m^3), A is the area swept by the turbine blades and U is the wind speed. The power coefficient (C_p) is a measure of the fraction of kinetic energy in the wind (P_{wind}) that is converted to mechanical energy via the turbine. Its value is a function of the tip speed ratio (λ), defined as

$$\lambda = \frac{Tip\ speed\ of\ blade}{Wind\ speed} = \frac{r\omega}{U} \qquad (2)$$

where r and ω are the rotor's radius and angular speed, respectively. For simplicity in determining the generator design parameters, it is assumed that it is possible to control the tip speed ratio such that maximum mechanical power conversion is achieved; therefore C_p will be considered constant at its maximum value.

During the research process, it has been discovered that there are discrepancies in the published literature as to what the maximum power coefficient is for the American multi-blade turbine structure. Fig. 2 shows a plot of power coefficients for different turbine structures that was taken from [6] and is also found in [10]; it demonstrates a $C_{p,max} \approx 0.15$ for the turbine of interest. A similar plot is included in [12], [17] and [18], however the curves for the Savonius and multi-blade rotors are transposed; these show a $C_{p,max} \approx 0.3$ for the water-pumping windmill. Experimental data in [3] and [15] as well as theoretical calculations in [11] indicate that the power coefficient of the Savonius rotor turbine does indeed peak at around 30%, though it is, of course, dependent upon the specific blade geometry. Furthermore, measured data (adopted from Aeromotor Co.) regarding the water pumping capacities for various rotor and pump cylinder diameters and flow rates for wind speeds between 7 and 9 m/s can be found in [7]. From this data, the pump power output has been calculated and averaged over the pump specifications for each size turbine and the maximum conversion efficiency is determined based on the available wind power (Table I). The average efficiency (over all turbine sizes) of the total system is ~11%. If it is assumed that the pump and gear box have a combined efficiency of ~80%, then the average power conversion coefficient (C_p) of the turbine itself is ~14%. In conclusion, a maximum C_p of 15% is assumed for the purposes of this design exercise; however, it is the authors' recommendation that experimental aerodynamic measurements be performed on these multi-bladed turbines in order to verify or disprove this assumption.

An additional consideration in the determination of the generator design parameters is regarding the wind speed profile. One common tactic is to assume that the wind speed adheres to a Raleigh distribution, with a probability density function expressed as:

$$p(U) = \frac{\pi}{2}\left(\frac{U}{\bar{U}^2}\right) exp\left(-\frac{\pi}{4}\left(\frac{U}{\bar{U}}\right)^2\right) \tag{3}$$

where $\bar{U}$ is the mean wind speed. The convenience of this lies in that the probability of occurrence for any wind speed (U) can be calculated with knowledge of only the mean wind speed. The majority of the state of Nebraska is a class 3 wind site and so at a height of 10 m (approximate tower height for the 8-ft. diameter turbine), the mean wind speed falls between 5.1 and 5.6 m/s [9]. The wind speed distribution is shown in Fig. 3; the vertical axis values are scaled by a factor of hours per year in order to more readily interpret the data. The maximum mechanical power output of the turbine for any wind speed is calculated via Eq. 1 and multiplied by the probability of occurrence for that speed (Eq. 3) to obtain the power density curves that are also shown in Fig. 3.

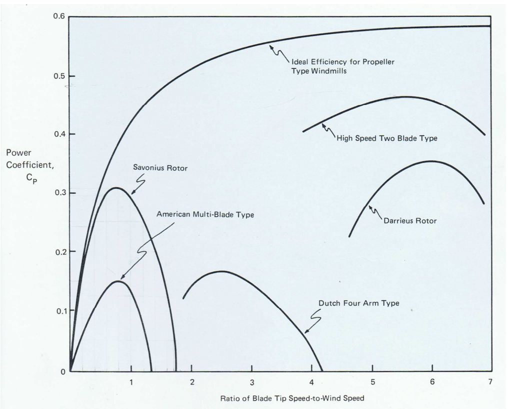

Figure 2. Power coefficient versus tip speed ratio for various turbine structures as given in [5].

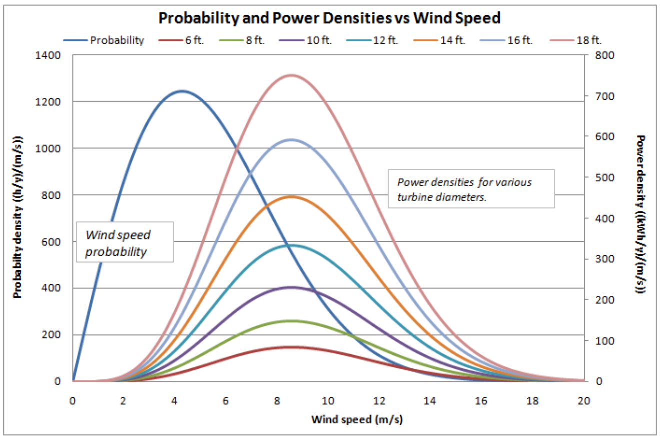

Figure 3. Probability and power density as a function of wind speed for different turbine sizes. Both curves sets are scaled by 8760 hours per year and the probability distribution shown is for a mean wind speed of 5.35 m/s.

TABLE I. POWER OUTPUT AND EFFICIENCIES OF WATER PUMPING WINDMILL SYSTEMS

Parameter	**Rotor Diameters**				
	8 ft.	***10 ft.***	***12 ft.***	***14 ft.***	***16 ft.***
Pump power output (W)	98	147	219	314	510
Wind power input (W)	939	1467	2112	2875	3755
System effficiency (%)	10.4	10.1	10.4	10.9	13.6

NOTE 1 — Based on data listed in [7] from Aeromotor Co.
NOTE 2 — The wind power input is calculated for a wind speed of 7 m/s.

TABLE II. POWER AND ANNUAL ENERGY OUTPUT OF THE TURBINES AVAILABLE FROM DEMPSTER INDUSTRIES, LLC.

Parameter	**Rotor Diameters**						
	6 ft.	***8 ft.***	***10 ft.***	***12 ft.***	***14 ft.***	***16 ft.***	***18 ft.***
P_{max} (W)	85	150	230	330	450	590	750
P_{max} (W)	70	125	195	280	385	500	635
Energy (kWh/y)	615	1095	1710	2450	3370	4380	5560

NOTE 1 — P_{max} is calculated via Eq. 1 for a wind speed of 8.5 m/s.
NOTE 2 — *Energy* indicates the integral of the power density curves shown in Fig. 3.
NOTE 3 — P_{ave} indicates the integral of the power density curve, rescaled to W.

The wind speed at which the power density curve peaks indicates the speed for which the majority of energy conversion occurs. Thus, as seen in Fig. 3, the generator should be designed to operate most efficiently at a wind speed of 8.5 m/s. The optimal tip speed ratio for these turbines falls just under unity (Fig. 2). Accordingly, if it is assumed that λ_{pk} has a value of 0.95, the nominal wind speed corresponds to a rotational speed of 65 rpm for the 8-ft diameter rotor. Each power density curve can be integrated over wind speed to yield the annual energy production for each turbine size; equivalently, the value of the integral can be rescaled (by hours per year as before) to yield the average turbine power output. These values are shown in Table II, along with the maximum mechanical power output for each turbine at a wind speed of 8.5 m/s. This analysis results in the nominal sizing characteristics for the generator of 265 W at a turbine speed of 65 rpm.

III. GENERATOR DESIGN

A. *Electric Machines in Wind Energy Conversion Systems*

By far the most common type of electric machine currently used in wind energy conversion systems is the induction machine. This is a well-established machine topology and is therefore relatively cheap and simple to manufacture. The doubly-fed induction generator (DFIG) is often preferred over the more traditional singly-excited (squirrel-cage) type because it is possible to operate DFIGs at variable speed for fixed electrical frequency, while concurrently maintaining efficiency. This is accomplished by the addition of a rotor-side power electronic interface to the grid to extract and process the slip power. This technology necessitates a gearbox in order to step-up the rotational speed of the turbine rotor (i.e. 60 rpm) to a speed more suitable for a 60 Hz generator (i.e. 1800 rpm for a 4-pole machine).

The DFIG system configuration is well-suited to large-scale wind applications where the system complexity is dwarfed by its size. A more viable option for small wind applications, and one that has recently garnered much research attention, is to make use of a direct-drive generator. The need for a gearbox is eliminated, thereby increasing system reliability and reducing costs associated with maintenance. Machines designed for direct-drive operation are typically larger for a given power output and naturally require a high pole count because they operate at very low rotational speeds [5]. Permanent-magnet machines are the most common choice for direct-drive wind applications due to the ease at which these high pole counts can be achieved [16]. Thus, for the application considered here, the generator is chosen to be a direct-drive, permanent-magnet synchronous machine (PMSM). Note that the power electronics and associated controls alluded to in Fig. 1 are necessary to cope with the variable speed nature of the system.

B. *Machine Topology*

PMSMs can be most broadly categorized into radial flux (RF) or axial flux (AF) topologies. A comprehensive comparison between these structures is daunting due to the sheer number of variables involved. However, it has been shown that for a given power requirement, when compared with an inner-rotor RF machine, an AF machine does have a lower mass and takes up less volume when the machine axial length is short and the pole count is adequately high [4,14].

This means that for a given power requirement, the AF machine will have a lower materials cost than an equivalent RF machine. Additionally, as a consequence of the AF slot geometry, the phase coils are planar which makes it very simple to form the coils around an external bobbin and slide them onto the teeth (Fig. 4). This last point may prove to be of importance for this application in which relatively low-volume production is expected and specialized manufacturing equipment may not be available.

AF machines can be designed as either single-sided, in which there is a single rotor disk, or double-sided, in which there are either two rotor disks (with a single stator) or two stator disks (with a single rotor) as seen in Fig. 4. It is shown in [14] that the single-sided machine has a much higher torque density, in terms of torque per unit active material mass, than its double-sided counterparts. For this application, there has not been a constraint placed on the outer radius of the generator and so the design will focus on the single-sided AF structure. The primary concern with the implementation of this machine type is that there is a very large axial attractive force between the stator and rotor; however, if sized correctly, standard deep groove ball bearings can easily be used to cope with this load.

The use of non-overlapped windings (NOW) in lieu of traditional winding schemes has become prevalent in recent years because of the benefits in terms of copper loss, fault-tolerance and manufacturability, among others (Fig. 4 shows a machine with a single-layer NOW). However, it has been recognized that a result of employing a NOW scheme is a higher harmonic content in the winding MMF distribution and a subsequent reduction (albeit slight) in the winding factor of the main harmonic as seen in Table III. These harmonics

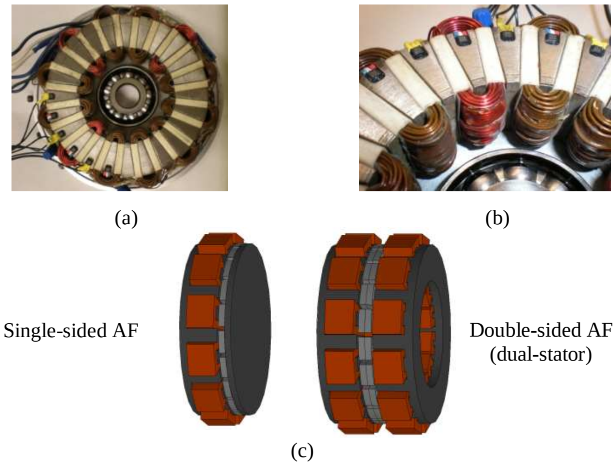

Figure 4. (a) Photograph of a sample AF machine stator and (b) a close-up to show the planar nature of the (non-overlapped) coils. Conceptual drawings of both a single-sided AF machine and dual stator double-sided AF machine are shown in (c).

TABLE III. MAIN HARMONIC WINDING FACTORS FOR SEVERAL COMMON SLOT-POLE COMBINATIONS

Slot-Pole Combination	**Winding Factor**
9-slot/8-pole	0.946 (DL)
9-slot/12-pole	0.866 (DL)
12-slot/8-pole	0.866 (DL)
12-slot/10-pole	0.966 (SL), 0.933 (DL)
12-slot/14-pole	0.933 (DL)
NOTE — SL denotes a single-layer winding in which there is a coil placed around every other tooth and DL denotes a double-layer winding in which there is a coil around every tooth.	

rotate asynchronously with the rotor and cause an increase in eddy-current loss there [2]; however, AF machines typically employ open slots whereby the rotor loss due to slotting swamps the loss associated with MMF harmonics, so this is not of primary concern in the context of this application.

C. Design Specification

The sizing of any electric machine is based upon a torque specification. As described in section II, the nominal operating point for this generator is an input of 265 W at a speed of 65 rpm, indicating a torque requirement of 39 Nm. Torque (τ) is commonly expressed as a function of the electromagnetic air-gap shear stress (σ), air-gap surface area (A) and the average air-gap radius (R_{av}) as:

$$\tau = \sigma \cdot A \cdot R_{av}. \tag{4}$$

For an axial-flux machine, it has been shown that peak performance occurs when the inner radius is approximately 60% of the value of the outer radius [8]. Substituting this constraint into Eq. 4, an expression to calculate the machine outer radius is obtained:

$$R_o = \sqrt[3]{\frac{\tau}{0.512\pi\sigma}} \tag{5}$$

Then, assuming an air-gap shear stress of 8 kPa, this generator would have an outer diameter of 290 mm (11.4”) and an inner diameter of 174 mm (6.9”). It is typical to design around a shear stress on the order of 15 kPa; however, because this is a high torque, low speed application, the low shear stress value facilitates copper loss management for operation at rated torque.

In order to ease manufacturing effort, it is preferred to have a slot-pole combination that can be fit with a single-layer winding. The 12-slot/10-pole configuration is selected as the base for this generator design because it offers the highest winding factor as indicated in Table III. As previously described, because the generator is directly coupled to the turbine rotor, the machine must be designed with a high pole count. The chosen geometry is summarized in Table IV. The bulk material cost is calculated using base costs of $1.50/kg for steel, $4.40/kg for copper and $38.00/kg for the magnet material (NdFeB), but these numbers are obviously susceptible to market fluctuations.

TABLE IV. GENERATOR DESIGN PARAMETERS

Parameter	**Generator**	
	Direct-drive	***Geared (5:1)***
Rated speed	65 rpm	325 rpm
Rated torque	38.9 Nm	7.8 Nm
Outer diameter	290 mm	170 mm
Inner diameter	174 mm	102 mm
Axial machine length	49 mm	39 mm
Airgap	1 mm	1 mm
Magnet thickness	4 mm	4 mm
Rotor back-iron thickness	4 mm	4 mm
Slot width	7.6 mm	8.9 mm
Slots	48	24
Poles	40	20
Material mass	14 kg	4 kg
Bulk material cost	$69.55	$22.07

For comparison, the same generator design has also been performed for the case when a small 5:1 gear system is included between the turbine rotor and the machine. Both designs are for the same power rating and are designed with the same airgap shear stress. The gearbox introduces additional cost and maintenance requirements to the system, but results in a generator design with approximately 70% lower mass and cost. For the designs detailed, the copper loss at rated torque is estimated to be around 30 W for the direct-drive design and 20 W for the higher speed machine. There will be additional inefficiency in the latter system due to the gearbox, however there is currently research being done in the field of magnetic gears that may be of interest for small wind applications [1].

IV. CONTINUING WORK

In this paper, an initial generator design is presented for a small-wind, direct-drive application. Before the design can be finalized, the electrical system requirements must be determined such that the generator, power electronics and associated control algorithms form a coherent unit. Additionally, the work presented here is based entirely on electromagnetic considerations and so some augmentations may be necessary in order to mechanically fit the generator to the windmill structure.

The generator presented in Table IV is based around a specific operating point as described previously. However, the machine should be able to operate in wind speeds up to 30 mph (the windmills are mechanically regulated to turn out of the wind at this speed). Therefore investigations into the survivability of the machine must be conducted. At the same time, it may be desirable to redesign the machine to reduced cost, although this will most likely result in reduced performance (efficiency) of the machine.

CONCLUSIONS

The concept of retrofitting electrical generation capabilities to existing water-pumping windmills has been examined. It has been found that little experimental data has been collected regarding multibladed windmill turbine performance and there are discrepancies in the literature regarding mechanical efficiencies. The mechanical structure of these turbines is optimized to provide high torque at low rotational speed, which makes electrical generation difficult. However, it has been shown that a direct-drive generator can be designed to fit the specifications, though it does result in a relatively large and costly machine. Ultimately, any limitations encountered in this project will not be technological, but economical.

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