Optimal Drive And Machine Sizing For A Self Starting, Vertical Axis, Low Power Wind Generator

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Nicola Bianchi, Silverio Bolognani, Emanuele Fornasiero, Giorgio Pavesi and Mattia Morandin

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IEEE - International Energy Conference & Exhibition (ENERGYCON 2012)

held in Florence, Italy, 9-12 September 2012
The EDLab is involved in a project, of the national program INDUSTRIA 2015, called PIACE. Industria 2015 provides the strategic development and competitiveness of Italian industry of the future. PIACE is about domestic cogeneration systems combined with renewable energies. It involves 22 partners from Universities and Companies, 6 of which involved on micro wind turbine topic.

**Project idea**

Low power wind application for installation in urban areas
Aim of the study

- Comparison between an **IPM** and an **SPM** generator (with drive) coupled with a **low power wind generator**
- **A Vertical axis wind turbine** is considered:
  - The turbine is omni-directional
  - Darrieus turbine coupled to a Savonius turbine to realize a self–starting turbine
- **A cost analysis** has been done to the aim of evaluating the **convenience of the system** in terms of total profit and pay–back time
The combined turbine is constituted by:

- **Savonius** turbine (diameter of 0.3\(m\))
- **Darrieus** turbine (diameter of 1.9\(m\) and height of 3\(m\))
Introduction

Aim of the study

Wind turbine optimization criteria

Optimization results

Machine design

Conclusions

Combined wind turbine

\[ \lambda = \frac{D_t \omega_m}{v_{wind}} \]
Combined wind turbine

Coefficient of power vs. Tip speed ratio graph showing the performance comparison between a Combined and Darrieus turbine. The graph indicates higher efficiency at specific tip speed ratios for the Combined turbine compared to the Darrieus turbine.
Reference case

MPPT until $v_{wind} = 12\text{ m/s}$, then **stall**
MPPT until $v_{\text{wind}} = 12 \text{ m/s}$, then **stall**
MPPT until $v_{\text{wind}} = 12 \text{ m/s}$, then stall
Reference case

MPPT until $v_{wind} = 12\, m/s$, then \textit{stall}
In order to optimize the design, some **limitations** can be introduced to reduce the initial cost of the system.

The **maximum profit**, without penalizing the **payback–time**, is chosen as the optimization objective.
Example of application of the limits
Assumptions:

- **Weibull statistics** used as base for wind probability: parameters $k = 1.4$ and $v_{avg} = 4.5 \text{m/s}$
- **MPPT tracking** algorithm to maximize the power up to $v_{wind} = 12 \text{m/s}$
- **Mechanical brake** to stop the turbine at maximum speed ($v_{wind_{max}} = 15 \text{m/s}$)
- Estimated efficiency of 90% for both generator and converter

The proposed analysis can be promptly arranged for any different system parameters
Assumptions for cost analysis:

- Energy remunerated for 10 years;
- **Electric generator cost** $\propto$ rated torque
- **Power converter cost** $\propto$ rated power
- **Turbine mechanical cost** $\propto$ maximum torque $\times$ maximum speed

$\Rightarrow$ Initial cost:

$$C_{\text{initial}} = c_{\text{gen}} T_{\text{max}} + c_{\text{el}} P_{\text{max}} + c_{\text{mec}} T_{\text{MPPT}} n_{\text{max}}$$

<table>
<thead>
<tr>
<th>index</th>
<th>cost</th>
<th>price</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_e$</td>
<td>0.4</td>
<td>€/kWh</td>
<td></td>
</tr>
<tr>
<td>$c_{\text{gen}}$</td>
<td>22</td>
<td>€/Nm</td>
<td></td>
</tr>
<tr>
<td>$c_{\text{el}}$</td>
<td>0.6</td>
<td>€/W</td>
<td></td>
</tr>
<tr>
<td>$c_{\text{mec}}$</td>
<td>0.04</td>
<td>€/(Nm $\times$ rpm)</td>
<td></td>
</tr>
</tbody>
</table>
IPM optimization result

Maximum rotor speed: 185% of reference case
**SPM optimization result**

Maximum rotor speed: 120% of reference case
### Optimization results

#### Economical results

<table>
<thead>
<tr>
<th></th>
<th>Reference machine</th>
<th>Optimized SPM</th>
<th>Optimized IPM</th>
<th>Unit of measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best torque</td>
<td>–</td>
<td>70</td>
<td>50</td>
<td>% $T_{ref}$</td>
</tr>
<tr>
<td>Best power</td>
<td>–</td>
<td>70</td>
<td>50</td>
<td>% $P_{ref}$</td>
</tr>
<tr>
<td>Best speed</td>
<td>–</td>
<td>120</td>
<td>185</td>
<td>% $\omega_{ref}$</td>
</tr>
<tr>
<td>System price</td>
<td>2.50</td>
<td>1.87</td>
<td>1.63</td>
<td>[k€]</td>
</tr>
<tr>
<td>Total profit</td>
<td>2.10</td>
<td>2.22</td>
<td>2.51</td>
<td>[k€]</td>
</tr>
<tr>
<td>Payback time</td>
<td>5.42</td>
<td>4.57</td>
<td>3.94</td>
<td>[years]</td>
</tr>
</tbody>
</table>
Optimization results

SPM working points

Power vs speed

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ENERGYCON 2012
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Machine design
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Optimization results

SPM working points

Power vs speed

\[ 	ext{Power} \text{ [W]} \]

\[ \text{Rotor speed} \text{ [rpm]} \]

REF.\text{. Working point}
SPM Working point
SPM Characteristic

\( v_{\text{wind}} = 11 \text{ m/s} \)
SPM working points

Power vs speed

- REF. Working point
- SPM Working point
- SPM Characteristic

$v_{\text{wind}} = 11.3 \text{ m/s}$
Optimization results

SPM working points

Power vs speed

\[ v_{\text{wind}} = 12 \text{ m/s} \]

- REF. Working point
- SPM Working point
- SPM Characteristic

Rotor speed [rpm]

Power [W]
SPM working points

Power vs speed

- REF. Working point
- SPM Working point
- SPM Characteristic

$v_{\text{wind}} = 15 \text{ m/s}$

Optimized Drive And Machine Sizing For A Self Starting, Vertical Axis, Low Power Wind Generator
Optimization results

IPM working points

Power vs speed

- REF. Working point
- IPM Working point
- IPM Characteristic

$\nu_{\text{wind}} = 8.5 \text{ m/s}$
IPM working points

Power vs speed

- REF. Working point
- IPM Working point
- IPM Characteristic

$\nu_{\text{wind}} = 10 \text{ m/s}$

Rotor speed [rpm]

Conclusions
IPM working points

Power vs speed

\[ v_{\text{wind}} = 12 \text{ m/s} \]

- REF. Working point
- IPM Working point
- IPM Characteristic

Rotor speed [rpm]

Power [W]
Optimization results

IPM working points

Power vs speed

$\nu_{\text{wind}} = 15 \text{ m/s}$

$\nu_{\text{wind}} = 15 \text{ m/s}$

REF.

IPM

Rotor speed [rpm]

Power [W]
### Machine design

<table>
<thead>
<tr>
<th></th>
<th>SPM</th>
<th>IPM</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air–gap diameter</td>
<td>71</td>
<td>71</td>
<td>[mm]</td>
</tr>
<tr>
<td>External diameter</td>
<td>133.5</td>
<td>133.5</td>
<td>[mm]</td>
</tr>
<tr>
<td>Stack length</td>
<td>118</td>
<td>95</td>
<td>[mm]</td>
</tr>
<tr>
<td>Slot current density</td>
<td>6</td>
<td>6</td>
<td>[$A_{rms}/mm^2$]</td>
</tr>
<tr>
<td>Rated torque</td>
<td>28</td>
<td>19</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Base speed</td>
<td>415</td>
<td>415</td>
<td>[rpm]</td>
</tr>
<tr>
<td>PM weight</td>
<td>0.645</td>
<td>0.3</td>
<td>[kg]</td>
</tr>
<tr>
<td>Iron weight</td>
<td>7.5</td>
<td>7.2</td>
<td>[kg]</td>
</tr>
<tr>
<td>Copper weight</td>
<td>2.25</td>
<td>1.91</td>
<td>[kg]</td>
</tr>
<tr>
<td>Total weight</td>
<td>10.4</td>
<td>9.4</td>
<td>[kg]</td>
</tr>
</tbody>
</table>
An economical comparison have been proposed for two cases of low power wind generator applied to a VAWT: a SPM and an IPM machine.

Torque, power and speed limits have been introduced to reduce the initial cost of the whole system.

Both the cases of study present an improvement in terms of cost of the system, compared with the cost of the reference case (i.e without the above limits).

Even if there is a loss of energy productivity, an optimal solution can be found, which maximizes the profit with a reduced payback time.

An effective profit–payback time chart is proposed to point out the optimal solution.
N. Bianchi and A. Lorenzoni,

M. Morandin, E. Fornasiero, S. Bolognani, and N. Bianchi,
N. Bianchi and S. Bolognani,
Thank you for your attention