A wind farm electrical systems evaluation with EeFarm-II

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Part 1: Wind farm electrical system evaluation

1. main WF specifications (size, location, distance shore etc.)
2. input power per WT and wind speed / direction
3. choice of electrical components (type: AC or DC, size)
4. choice of layout (location of cables and central platform)
5. preparation of steady state (load flow/voltage drop) model
   - voltages and currents in all components
   - electric losses
   - non-availability calculation (location dependant)
6. energy production for operating range
7. levelised production costs (LPC)

- system modification to improve LPC
AC component models

- AC controllable source
- Generators:
  - Induction
  - Doubly Fed Induction
  - Full Converter Induction
  - Generic
- AC cable
- Transformer
  - fixed voltage ratio
  - variable ratio: automatic tapchanger
- Inductor
- AC node and splitter
DC component models

- Pulse Width Modulated (PWM) converter
  - TUD model
  - Kazmirkovsky model
  - Infineon model
- Thyristor converter
- DC cable
  - monopolar
  - bipolar
- Upchopper (DC-DC converter)
- Statcom
- DC node and splitter
Control

- reactive power feedback
  sets turbine reactive power
  for zero reactive power at PCC
- automatic tap changer
  improves voltage profile
Database

- component properties and parameters:
  - manufacturer and type
  - rated voltage and current
  - electrical parameters (R, L, C, tandel, etc)
  - budget price supplied by manufacturer
- combined in a single variable (Matlab structure)
- loaded by a user specified Matlab file
Making an EeFarm model is easy: copy block from library and connect.
Postprocessing

- automatic calculation of
  - wind speed distribution dependent energy production
  - levelised production cost (LPC)
- automatic generation of characteristic output tables
  - max Pout, Ploss, Pfail (MW and %)
  - max Pnett (MW)
  - Etot (MWh/y), Eloss, Efail (MWh/y and %)
  - Pav (MW), CF
  - LPC (Euro/kWh)
- automatic generation of characteristic plots
Part 2: Case study

- 200 MW wind farm with 5 MW wind turbines
- 100 km distance to shore
- 2 wind farm layouts:
  - strings of 5 turbines (daisy chain)
  - stars of 9 turbines with 1 at center
- central platform
- 4 types of electrical systems:
  - constant speed, all AC systems (C1, C2)
  - individual variable speed, AC to shore (IV1-IV5)
  - cluster variable speed, DC to shore (CV1-CV4)
  - park variable speed, DC to shore (PV1, PV2)
Constant speed, all AC
Individual variable speed, AC connected
Individual variable speed, HVDC connected

IV3

IV4

IV5
Cluster variable speed, HVDC connected
Cluster variable speed, HVDC + upchopper
Park variable speed
## Results

<table>
<thead>
<tr>
<th></th>
<th>Voltage (kV)</th>
<th>Current (A)</th>
<th>Power (MW)</th>
<th>Reactive Power (MVA)</th>
<th>Losses (MW)</th>
<th>Relative losses (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>133</td>
<td>902</td>
<td>189.2</td>
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<td>903</td>
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<td>813</td>
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<td>20.6</td>
<td>0.1031</td>
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<td>PV1</td>
<td>143</td>
<td>718</td>
<td>177.9</td>
<td>-11.9</td>
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<td>0.1104</td>
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<tr>
<td>PV2</td>
<td>141</td>
<td>732</td>
<td>177.9</td>
<td>-12.4</td>
<td>22.1</td>
<td>0.1105</td>
</tr>
</tbody>
</table>
Losses at maximum power (100km)

dark blue = cables in farm
blue = cluster trafos
light blue = rectifiers
orange = transformers
red = inductors
green = inverters
green-blue = choppers
brown = cables to shore

Losses (%)

C1  C2  IV1  IV2  IV3  IV4  IV5  CV1  CV2  CV3  CV4  PV1  PV2
Remarks

• losses depend on voltage level and type of component (AC, DC)
• IV3, IV4 and IV5 have DC in farm and AC to shore
• all CV and PV systems have DC to shore
• transformer losses not negligible
  (may be too high due to upscaling)
• DC (+/-80kV) cable losses slightly higher than AC (150kV)
• systems with DC have relatively high losses caused by
  – extra transformer losses
  – converter losses
    (converter losses compatible with independent info)
  – relatively high DC cable losses
## Results: Energy Production

<table>
<thead>
<tr>
<th></th>
<th>Energy produced (MWh/y)</th>
<th>Energy losses (MWh/y)</th>
<th>Relative losses (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>938940</td>
<td>55638</td>
<td>0.0593</td>
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<tr>
<td>C2</td>
<td>936141</td>
<td>58437</td>
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<tr>
<td>IV1</td>
<td>937275</td>
<td>57303</td>
<td>0.0611</td>
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<tr>
<td>IV2</td>
<td>934051</td>
<td>60527</td>
<td>0.0648</td>
</tr>
<tr>
<td>IV3</td>
<td>923253</td>
<td>71341</td>
<td>0.0773</td>
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<tr>
<td>IV4</td>
<td>917979</td>
<td>76611</td>
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<tr>
<td>IV5</td>
<td>915285</td>
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<td>0.0866</td>
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<td>CV1</td>
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<tr>
<td>CV2</td>
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<tr>
<td>CV3</td>
<td>897070</td>
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<td>0.1087</td>
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<tr>
<td>CV4</td>
<td>896641</td>
<td>97913</td>
<td>0.1092</td>
</tr>
<tr>
<td>PV1</td>
<td>889702</td>
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<td>0.1178</td>
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<tr>
<td>PV2</td>
<td>891353</td>
<td>103189</td>
<td>0.1158</td>
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</tbody>
</table>
Remarks

- DC cables relatively cheap compared to equivalent AC
- counteracted by converter investment costs
- platform costs are considerable, especially for transformer + converter
- IV3-IV5 combine DC in farm with AC cable to shore
  - DC cables (+/-80kV, 65MW) in farm relatively expensive
  - AC cable to shore relatively expensive
- DC-DC choppers very expensive (not standard)
- systems with DC in farm (IV3, IV4, IV5) or DC-DC converter: high investment costs

- investment costs of C1, C2 about same as PV1, PV2 (100km/200MW)
## Investment and LPC

<table>
<thead>
<tr>
<th></th>
<th>Investment (MEuro)</th>
<th>Energy produced (MWh/y)</th>
<th>Specific investment (MEuro/MW)</th>
<th>LPC (Euro/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>110.6</td>
<td>935227.7</td>
<td>0.5530</td>
<td>0.0137</td>
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<td>C2</td>
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<tr>
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<tr>
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<tr>
<td>IV4</td>
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<tr>
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<td>PV1</td>
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<tr>
<td>PV2</td>
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<td>0.5680</td>
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</tr>
</tbody>
</table>
Remarks

- LPC relatively high: economic life time only 12 y

- electrical component unavailability not included
  - effect substantial (few % of produced power)
  - depends on redundancy
  - what failure rate for offshore cables?

- voltage control not included
  - effect relatively small (few 0.1% of produced power)
Conclusion

wea@sea project EeFarm-II resulted in:

• a flexible (AC as well as DC), easy to use and fast computer program for WF electrical evaluation
• a comparison of 13 WF electrical systems
• a report with detailed model description
• a paper in the Energies Journal

• EeFarm-II is commercially available
• part of the database is confidential and not included in the supply
Questions or time for coffee?