Analytical and Data-Driven Methods for Determining Wind Farm Collector System Equivalent Impedance

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CIGRE Grid of the Future
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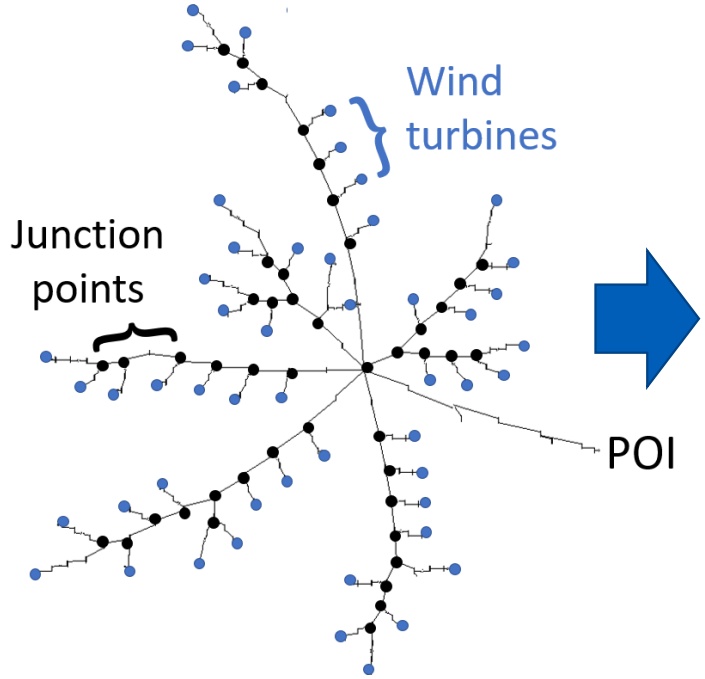
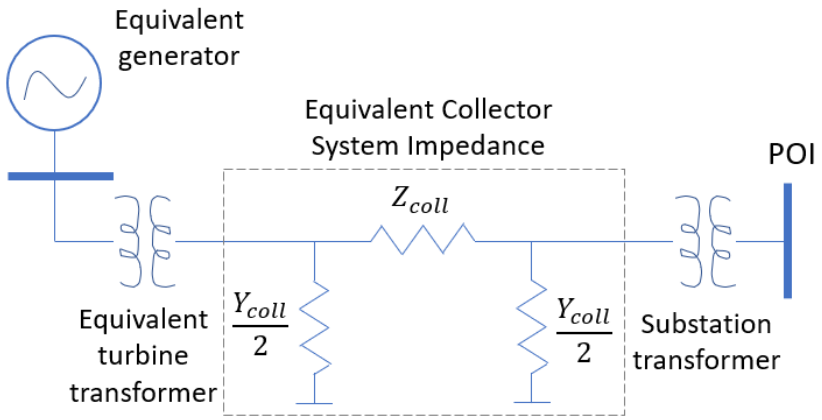
Wind Farm Collector System

The collector system connects and evacuates power from the individual wind turbines in the farm





For most modelling applications, an equivalent system is sufficient

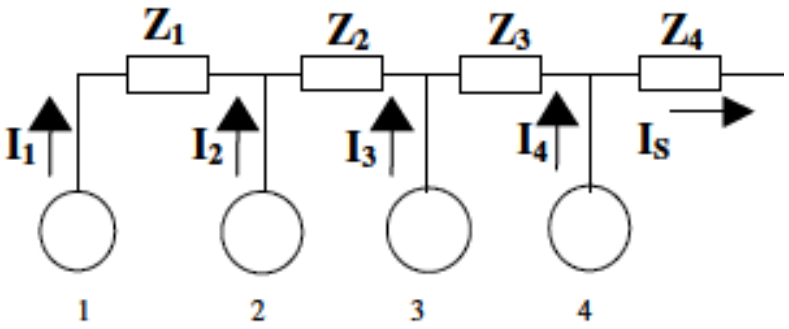
NREL Equivalencing Method

Industry standard method

Basic principle: equivalent losses $S_{Loss} = \sum_{cables} S_i = V_{coll}^2 Z_{eq} \rightarrow \boldsymbol{Z_{eq} = \frac{V_{coll}^2}{S_{Loss}}}$

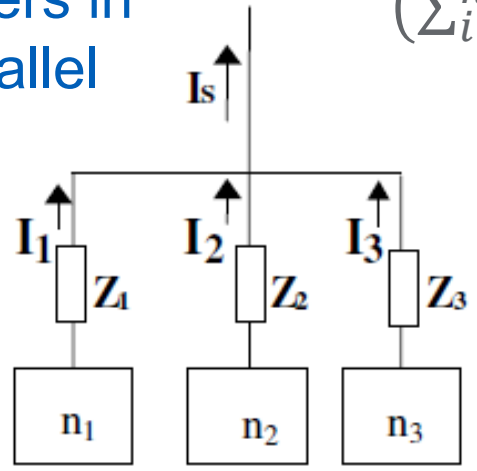
One feeder of turbines in series

$$Z_s = \frac{\sum_{i=1}^{n} i^2 Z_i}{n^2}$$



Multiple feeders in parallel

$$Z_P = \frac{\sum_{i=1}^{n} n_i^2 Z_i}{\left(\sum_{i=1}^{n} n_i\right)^2}$$



Shunt Susceptance

$$B_{eq} = \sum_{cables} B_i$$

E. Muljadi *et al.*, "Equivalencing the collector system of a large wind power plant," *2006 IEEE Power Engineering Society General Meeting*, Montreal, Que., 2006, pp. 9-18.

Drawbacks of the NREL Method

Solid analytical framework with two key challenges

1. Difficult to compute by hand
   - Wind farms up to ~100 turbines
   - Current on each branch must be determined

$$Z_s = \frac{\sum_{i=1}^{n} i^2 Z_i}{n^2} \qquad Z_P = \frac{\sum_{i=1}^{n} n_i^2 Z_i}{\left(\sum_{i=1}^{n} n_i\right)^2}$$

→ Graph theory-based algorithm

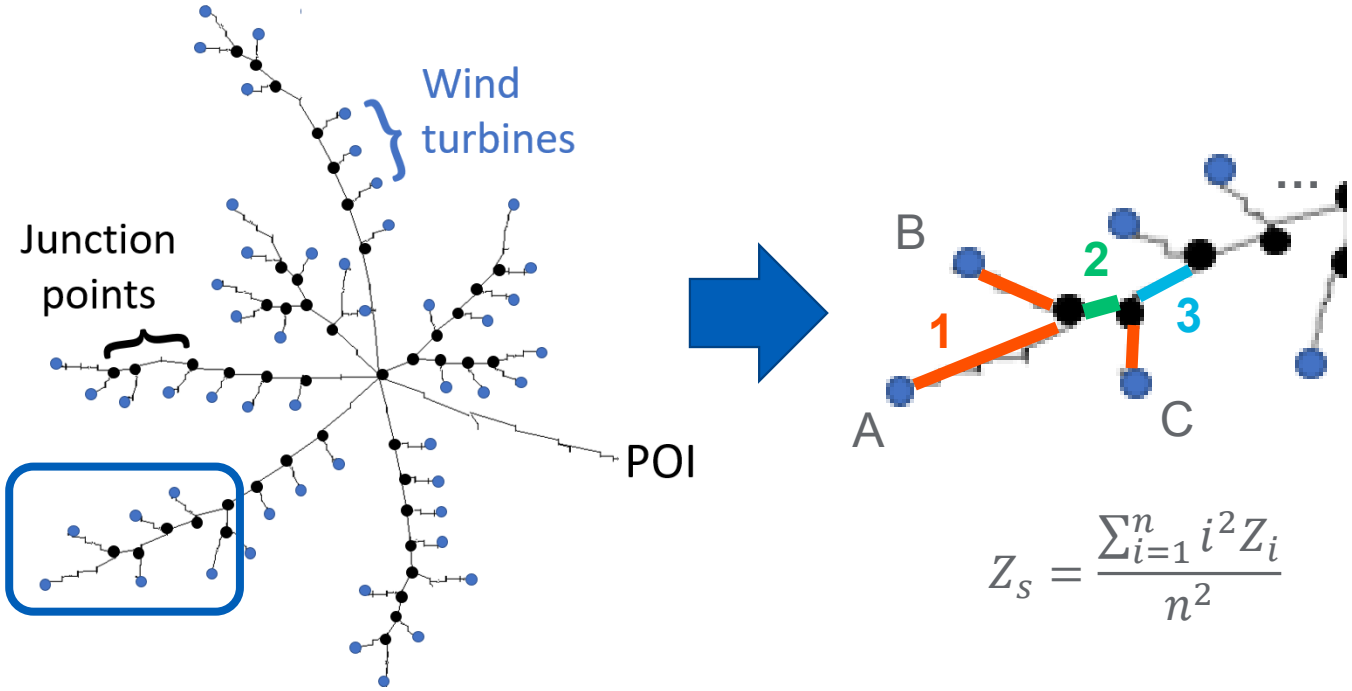
2. Requires detailed cable design
   - Impedance and shunt susceptance of every c

→ Data-driven estimation

Method 1: Graph Theory-based Algorithm

How can you equivalence large, complex wind farms?

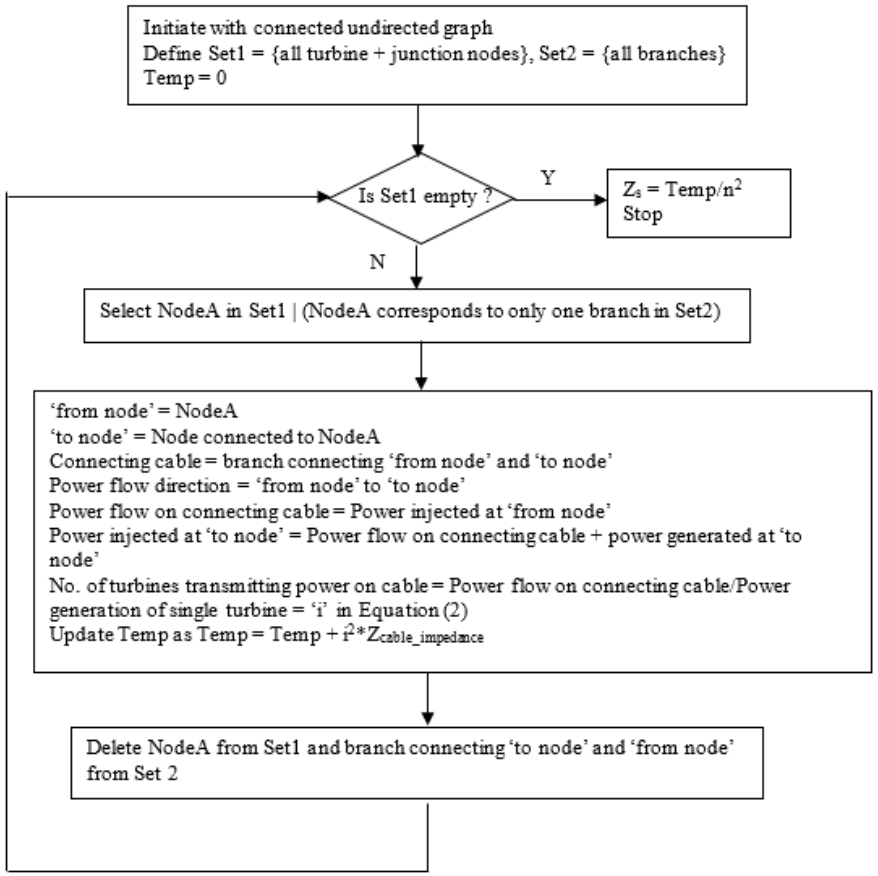
Consider the wind farm as an undirected, unweighted graph



$$Z_s = \frac{\sum_{i=1}^{n} i^2 Z_i}{n^2}$$

To equivalence, need to know current magnitude and direction on each branch (i.e. weighted, directed graph)

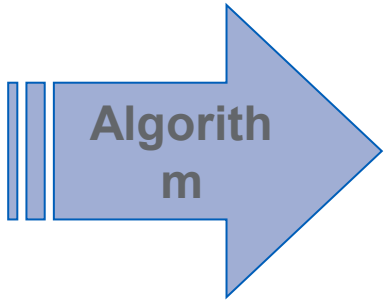
Algorithm Flow Chart



Method 1: Graph Theory-based Algorithm

Input: R,X,B values for branches between each of the nodes and identification of turbine nodes

From Node	To Node	R	X	B
1001	1002	0.01	0.01	0.001
1002	1003	0.015	0.03	0.002
⋮	⋮	⋮	⋮	⋮



Output: Weighted graph and equivalent R,X,B

```
  0.0034 + 0.0046i

============================================================
 FROM     TO            S=P+jQ          #turbs on segment
============================================================
 1001     1005     0.02212 + j0.00603          1
 1005     1006     0.09545 + j0.02409          2
 1006     1015     0.26271 + j0.12579          3
 1007     1010     0.02423 + j0.00660          1
 1010     1019     0.09337 + j0.02357          2
```

Automatically equivalences the collector system with 2 basic inputs

Method 2: Data-Driven Estimation

What if you don't have detailed cable data?

Two hypotheses:

1. Z ↓ as number of feeders ↑
2. Z and B ↑ as feeder length/geographical span ↑

Propose the following empirical formulas based solely on P

Developers should have farm MW rating, P, much before cable design

$$\hat{R}(P) = \alpha_R P + \beta_R \frac{1}{P} \qquad \hat{X}(P) = \alpha_X P + \beta_X \frac{1}{P} \qquad \hat{B}(P) = \alpha_B P + \beta_B \frac{1}{P}$$

Fit α and β based on real wind farm data

Here, data from 40 onshore wind farms with underground cables used to fit ordinary least squares model

	α	β
R	$1.8094 * 10^{-5}$	0.8378
X	$4.1655 * 10^{-5}$	1.2695
B	$1.7363 * 10^{-4}$	5.0640

Method 2: Data-Driven Estimation

Validation with three additional wind farms

Reactance, X

Farm#	$P\ [MW]$	$X\ [p.u.]$	$\hat{X}\ [p.u.]$	$\Delta\ [p.u.]$
2	136	0.0069	0.0086	0.0017

Resistance, R

Farm#	$P\ [MW]$	$R\ [p.u.]$	$\hat{R}\ [p.u.]$	$\Delta\ [p.u.]$
2	136	0.0081	0.0150	0.0069

Susceptance, B

Farm#	$P\ [MW]$	$B\ [p.u.]$	$\hat{B}\ [p.u.]$	$\Delta\ [p.u.]$
2	136	0.0363	0.0609	0.0246

- Valid up to three decimal places for some cases
- Follows correct trend in P
- Some points with poor fit
  - R and B are hard to measure accurately

Framework can be used and continuously improved with additional data and advanced regression techniques

Conclusion

- Collector system equivalent impedance is used for many modelling applications
- The NREL framework requires detailed data and can be difficult for large wind farms
- An analytical, graph theory-based algorithm can automatically equivalence the collector, simplifying an error-prone, manual process
- A data-driven model can estimate the impedance and susceptance using just the farm MW rating

Thank you!