

RADBOUD UNIVERSITY NIJMEGEN



FACULTY OF SCIENCE

Power Grid Failures

Theory of Fluctuating Renewables

THESIS BSC MATHEMATICS

Supervisor:

dr. Henk DON

Author:

Fons VAN DER PLAS

Second reader:

prof. dr. Eric CATOR

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Notation

\mathbf{Y} is a matrix or vector

$Y_{i,j}$ is an element of a matrix or vector

Y is a (real or complex) number

\mathbb{Y} is a physical quantity (like ‘admittance’)

$\bar{\mathbf{Y}}$ is the *element-wise complex conjugate* of \mathbf{Y}

\mathbf{Y}^* is the *adjoint* of \mathbf{Y} (which is equivalent to
the *transpose* for real-valued \mathbf{Y})

$[n] = \{1, \dots, n\}$

Een geel doosje geeft aan dat een stuk tekst *nog geschreven moet worden*.

Een oranje doosje is meer *voor mezelf*, dingen waar ik later nog naar moet kijken.

Een groen doosje geeft bronnen aan die relevant (kunnen) zijn.

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Part I

Theory of Electric Power Networks

Chapter one

Probability Theory

1.1 *Abstract Integration

Lebesgue-Stieltjes integral

See Rynne
or Garling
or Analyse
de Hilbert et
de Fourier
course notes

1.2 *Probability Measure

Should cover: p. measure, cont. distr., stochastic vectors, E , moment gen?, CLT,
multivar norm dist

See Pest-
man or MIT
course notes
or...

1.3 Large Deviation Theory

Should cover: application to multivariate normal dist

See Hugo or
MIT course
notes or ...

1.4 Multivariate Gaussian distribution

This presentation of the multivariate Gaussian distribution is heavily based on Chapter VIII of Mathematical Statistics by Pestman (1998), which provides proofs to all theorems listed below.

One distribution that will be particularly useful in our analysis is the *multivariate Gaussian distribution*, which generalised the (one-dimensional) normal distribution. In the simplest case, we have a stochastic vector $E = (E_1, \dots, E_p)$, which is the combination of p normally distributed, *independent* scalar variables. In general, however, we wish to study stochastic vectors produced by applying a *linear transformation* $L \in \mathcal{L}(\mathbb{R}^p, \mathbb{R}^q)$ to E . In this case, the coordinate variables $(LE)_1, \dots, (LE)_q$ are not always independent! For example, the map $(E_1, E_2) \mapsto (E_1, E_1 + E_2)$ transforms two independent normals into two dependent ones.

Deze inle-
ding slaat
het geval E
Gaussiaans
maar niet
normaal,
over.

1.4.1 Normal and Gaussian

Although they are often used interchangeably, we make a clear distinction between a *normal* distribution and a *Gaussian* distribution. The former should be familiar:

Definition 1.4.1. A scalar variable E is said to be *normally distributed* with parameters μ and σ if

$$x \mapsto \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right] \quad (1.1)$$

is the probability density of E .

Definition 1.4.2. A scalar variable E is said to be *Gaussian distributed* if it is either normally distributed or constant.

One could interpret a constant E with value μ as a normally distributed variable with mean μ and ‘standard deviation 0’. Clearly, a linear combination of Gaussian distributed scalar variables is also Gaussian distributed.

Definition 1.4.3. A stochastic vector $\mathbf{E} = (E_1, \dots, E_p)$ is *elementary normally distributed* if the scalar variables E_i are independent and normally distributed ($i \in [p]$). \mathbf{E} is *elementary Gaussian distributed* if the scalar variables E_i are independent and Gaussian distributed.

Definition 1.4.4. A stochastic vector $\mathbf{X} = (X_1, \dots, X_p)$ is *normally distributed* if there exists an orthogonal operator \mathbf{Q} such that $\mathbf{Q}\mathbf{X}$ is elementary normally distributed. \mathbf{X} is *Gaussian distributed* if there exists an orthogonal operator \mathbf{Q} such that $\mathbf{Q}\mathbf{X}$ is elementary normally distributed.

Plaatjes vullen gaatjes

We state, without proof, the following properties of Gaussian distributed vectors:

Proposition 1.4.5. The distribution of a Gaussian distributed vector \mathbf{X} is uniquely determined by its expectation $\boldsymbol{\mu} = \mathbb{E}[\mathbf{X}]$ and covariance matrix $\boldsymbol{\Sigma} = \mathcal{C}(\mathbf{X})$, and we write $\mathbf{X} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$. \mathbf{X} is normally distributed if and only if $\boldsymbol{\Sigma}$ is invertible.

define cov-mat

Translating or applying a linear map to a Gaussian distribution results in a new Gaussian distribution. Note that this can be *any* linear map, not necessarily a bijective, orthogonal one.

Theorem 1.4.6. Suppose \mathbf{X} is a $\mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ -distributed p -vector.

For any $\mathbf{a} \in \mathbb{R}^p$:

$$\mathbf{X} + \mathbf{a} \sim \mathcal{N}(\boldsymbol{\mu} + \mathbf{a}, \boldsymbol{\Sigma}), \quad (1.2)$$

and for any linear map $\mathbf{L} \in \mathcal{L}(\mathbb{R}^p, \mathbb{R}^q)$:

$$\mathbf{L}\mathbf{X} \sim \mathcal{N}(\mathbf{L}\boldsymbol{\mu}, \mathbf{L}\boldsymbol{\Sigma}\mathbf{L}^*). \quad (1.3)$$

positive def-
inite keer
normaal is
normaal

Corollary 1.4.6.1. For any $\mathbf{b} \in \mathbb{R}^p$, the mapping

$$\mathbf{b}^* : \mathbb{R}^p \rightarrow \mathbb{R} : \mathbf{x} \mapsto \langle \mathbf{x}, \mathbf{b} \rangle$$

is linear, and therefore the scalar variable $\mathbf{b}^* \mathbf{X} = \langle \mathbf{X}, \mathbf{b} \rangle$ is Gaussian distributed.

In particular, when applying Corollary 1.4.6.1 to each element of the standard basis $(\mathbf{e}_1, \dots, \mathbf{e}_p)$ of \mathbb{R}^p , we find that each of the coordinates of \mathbf{X} is Gaussian distributed:

Proposition 1.4.7. Suppose $\mathbf{X} = (X_1, \dots, X_p)$ is a $\mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ -distributed p -vector. Then each for each $i \in [p]$, the marginal distribution is given by:

$$X_i \sim \mathcal{N}(\mu_i, \Sigma_{ii}).$$

For normal distributed vectors, a probability density function exists:

Theorem 1.4.8. Suppose \mathbf{X} is a normally distributed p -vector with expectation $\boldsymbol{\mu} = \mathbb{E}[\mathbf{X}]$ and covariance matrix $\boldsymbol{\Sigma} = \mathcal{C}(\mathbf{X})$. Then \mathbf{X} has a probability density function given by

$$\mathbf{x} \mapsto \frac{1}{\sqrt{\det(\boldsymbol{\Sigma})} (2\pi)^{p/2}} \exp \left[-\frac{1}{2} (\mathbf{x} - \boldsymbol{\mu})^* \boldsymbol{\Sigma}^{-1} (\mathbf{x} - \boldsymbol{\mu}) \right] \quad (1.4)$$

Remark. The condition that \mathbf{X} is normally distributed is necessary: if \mathbf{X} is Gaussian, but not normal, it will take values in an *affine subspace* of \mathbb{R}^p (such as a plane, as subspace of \mathbb{R}^3). If a density function were to exist, it would have support of zero measure, and integrating over \mathbb{R}^p would yield 0, instead of 1.

Klopt dit?

Theorem 1.4.9. The mode of a Gaussian distribution is its mean.

(waar) moet dit?

1.4.2 One linear condition

Definition 1.4.10. Given a $\mathbf{r} \in \mathbb{R}^p$ and $b \in \mathbb{R}$, the set $A \subseteq \mathbb{R}^p$ of solutions to the equation

$$\langle \mathbf{r}, \mathbf{x} \rangle = b$$

is called a *plane* in \mathbb{R}^p . The set $B \subseteq \mathbb{R}^p$ of solutions to

$$\langle \mathbf{r}, \mathbf{x} \rangle \leq b$$

is a *half-space* in \mathbb{R}^p . When $b = 1$, we write \mathbf{r}_A , and we say that \mathbf{r}_A is a *pillar* for A . Two planes are called *parallel* if they do not intersect.

Remark. When $b \neq 1$, we can scale \mathbf{r} to create a pillar for A or B , unless $b = 0$ (which is the case if and only if $\mathbf{0} \in A, B$, respectively).

Remark. $A = \partial B$.

Orthogonal projection onto a plane

Definition 1.4.11. A *convex polyhedron* in \mathbb{R}^p is the intersection of finitely many half-spaces in \mathbb{R}^p , and can be written as the set of solutions to

$$\mathbf{R}\mathbf{x} \leq \mathbf{b},$$

where each i th row of \mathbf{R} , together with b_i , defines one of the intersecting half-spaces.

The boundary of a convex polyhedron is contained in the union of planes corresponding to the half-spaces. This relation is strict, in general.

The convex polyhedra in \mathbb{R} are exactly all (possibly infinite) closed intervals. Convex polyhedra in \mathbb{R}^3 are familiar shapes, like a cube or a pyramid, but they might also be unbounded, like a pyramid with infinitely deep foundations. Objects that are *not* convex polyhedra are spheres (no finite intersection of half-spaces) and donuts (not convex, which as the name suggest, is a property of any convex polyhedron¹).

In this thesis, we model the *power injection* of a grid as a normally distributed stochastic vector, where each coordinate corresponds to the amount of energy injected at a node of the network. Positive values denote net generation (injection) and negative values are assigned to net consumption. The stochastic behaviour originates from *renewable sources*: wind and solar, and their correlations arise from correlated weather.

The transmission network was built to transfer power from one node to another, i.e. have a non-zero power injection. In Chapter 4, we will learn that not all power injections are *feasible*, as some might cause one of the transmission lines to overload. The *feasibility region* (the set of power injections that can be used) is, to some approximation, a *convex polyhedron*.

Using historical generation series, we can estimate the covariance of this power injection. Because the amount of current flowing through a line is a linear function of the power injection (by the same approximation), we can use Corollary 1.4.6.1 to determine the marginal distribution of line current, which gives the probability of an overload failure. A failure of this kind (i.e. caused by a fluctuation of renewable injection) is called an *emergent failure*.

Current studies (notably Nesti et al. (2018a) and ?) take this one step further, by determining the *most probable power injection that caused the emergent failure to occur*. We follow the approach of Nesti et al. (2018a), which is generalised in the following Theorem. Here, the plane A can be taken to be one of the *boundary planes of the feasibility region, corresponding to one of the lines*, and the event $\mathbf{X} \in A$ is the *moment that this line overloads*.

Theorem 1.4.12. *Let $\mathbf{X} \sim \mathcal{N}(\boldsymbol{\mu}, \boldsymbol{\Sigma})$ be a normally distributed p -vector with density function $f_{\mathbf{X}}$, and let $A \subseteq \mathbb{R}^p$ be a plane, given by a pillar $\mathbf{r}_A \in \mathbb{R}^p$. Then $\mathbf{X} | A$ is Gaussian distributed, and has mode*

$$\tilde{\mathbf{x}}_A = \underset{\mathbf{x} \in A}{\operatorname{argmax}} f_{\mathbf{X}}(\mathbf{x}) = \boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\mu}, \mathbf{r}_A \rangle}{\langle \boldsymbol{\Sigma} \mathbf{r}_A, \mathbf{r}_A \rangle} \boldsymbol{\Sigma} \mathbf{r}_A. \quad (1.5)$$

Proof. We will start with the special case of $\boldsymbol{\Sigma} = \mathbf{I}$, and work our way towards the general case.²

Step 1. The case of unit covariance.

Suppose \mathbf{X} is *elementary* normally distributed, with all marginal variances equal to one, i.e. $\boldsymbol{\Sigma} = \boldsymbol{\Sigma}^{-1} = \mathbf{I}$. The probability density function of X (see Equation (1.4)) then reduces to:

$$\mathbf{x} \mapsto \frac{1}{(2\pi)^{p/2}} \exp \left[\frac{-\|\mathbf{x} - \boldsymbol{\mu}\|^2}{2} \right].$$

hier bestaat
vast notatie
voor

A is not an
event, but
 $\mathbf{X}^{-1}(A)$ is.

inproduct \mathbf{rx}
is verkeerd
om

¹Using the linearity of the inner product, one easily finds that half-spaces are convex, and so are their intersections.

²This process uses the so-called the *standardised form* of \mathbf{X} .

This is a *decreasing* function of the *distance between \mathbf{x} and $\boldsymbol{\mu}$* , and so its mode is obtained when this distance is minimum.

Because A is an affine subspace of \mathbb{R}^p , the distance between $\mathbf{x} \in A$ and $\boldsymbol{\mu}$ is minimum when \mathbf{x} is the *orthogonal projection* of $\boldsymbol{\mu}$ onto A , which is given by:

$$\tilde{\mathbf{x}}_A = \boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\mu}, \mathbf{r}_A \rangle}{\langle \mathbf{r}_A, \mathbf{r}_A \rangle} \mathbf{r}_A.$$

Step 2. The case of an arbitrary elementary normal distribution.

Let us drop the assumption that all marginal variances are equal to one. There exist $\lambda_1, \dots, \lambda_p \in \mathbb{R}_{>0}$ such that $\Sigma = \boldsymbol{\Lambda} = \text{diag}(\lambda_1, \dots, \lambda_p)$, and $\boldsymbol{\Lambda}^t = \text{diag}(\lambda_1^t, \dots, \lambda_p^t)$ for any $t \in \mathbb{R}$. With $t = -\frac{1}{2}$, we find that $\boldsymbol{\Lambda}^{-\frac{1}{2}}\mathbf{X}$ is elementary normally distributed, with mean $\boldsymbol{\Lambda}^{-\frac{1}{2}}$ and unit covariance matrix. Applying the same transformation $\boldsymbol{\Lambda}^{-\frac{1}{2}}$ to A yields a new plane, which has pillar $\boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A$ (not $\boldsymbol{\Lambda}^{-\frac{1}{2}}\mathbf{r}_A$!):

For each $\mathbf{x} \in \mathbb{R}^p$, we have

$$\mathbf{x} \in A \iff$$

$$\begin{aligned} \langle \mathbf{x}, \mathbf{r}_A \rangle = 1 &\iff \sum_{i=1}^p x_i r_{A,i} = 1 \iff \sum_{i=1}^p \lambda_i^{-\frac{1}{2}} x_i \lambda_i^{\frac{1}{2}} r_{A,i} = 1 \iff \\ \langle \boldsymbol{\Lambda}^{-\frac{1}{2}}\mathbf{x}, \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A \rangle = 1 &\iff \langle \boldsymbol{\Lambda}^{-\frac{1}{2}}\mathbf{x}, \mathbf{r}_{\boldsymbol{\Lambda}^{-\frac{1}{2}}(A)} \rangle = 1 \\ &\iff \boldsymbol{\Lambda}^{-\frac{1}{2}}\mathbf{x} \in \boldsymbol{\Lambda}^{-\frac{1}{2}}(A). \end{aligned}$$

Dit zijnde vari-anties, ge-bruikt sim-gasquared?

This means that the plane $\boldsymbol{\Lambda}^{-\frac{1}{2}}(A)$ is defined by the pillar $\boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A$.

We can now apply our earlier result, and we find:

$$\begin{aligned} \tilde{\mathbf{x}}_A &= \boldsymbol{\Lambda}^{\frac{1}{2}} \overbrace{\left(\boldsymbol{\Lambda}^{-\frac{1}{2}}\mathbf{x} \right)}_{\boldsymbol{\Lambda}^{-\frac{1}{2}}(A)} = \boldsymbol{\Lambda}^{\frac{1}{2}} \left(\boldsymbol{\Lambda}^{-\frac{1}{2}}\boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\Lambda}^{-\frac{1}{2}}\boldsymbol{\mu}, \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A \rangle}{\langle \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A, \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A \rangle} \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A \right) \\ &= \boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\Lambda}^{-\frac{1}{2}}\boldsymbol{\mu}, \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A \rangle}{\langle \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A, \boldsymbol{\Lambda}^{\frac{1}{2}}\mathbf{r}_A \rangle} \boldsymbol{\Lambda}\mathbf{r}_A = \boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\mu}, \mathbf{r}_A \rangle}{\langle \boldsymbol{\Lambda}\mathbf{r}_A, \mathbf{r}_A \rangle} \boldsymbol{\Lambda}\mathbf{r}_A. \end{aligned}$$

Step 3. The general case.

Finally, we consider the general case where \mathbf{X} is normally distributed. If so, there exists orthogonal \mathbf{Q} such that $\Sigma = \mathbf{Q}\boldsymbol{\Lambda}\mathbf{Q}^{-1}$, with $\boldsymbol{\Lambda}$ a diagonal matrix. In other words, the orthogonal map \mathbf{Q}^{-1} maps \mathbf{X} into an *elementary* normally distributed vector.³ Applying the same transformation \mathbf{Q}^{-1} to A yields a new plane, which is defined by the pillar $\mathbf{Q}^{-1}\mathbf{r}_A$. This derivation is more straightforward, since \mathbf{Q}^{-1} is orthogonal:

For each $\mathbf{x} \in \mathbb{R}^p$, we have

$$\mathbf{x} \in A \iff$$

$$\langle \mathbf{x}, \mathbf{r}_A \rangle = 1 \iff \langle \mathbf{Q}^{-1}\mathbf{x}, \mathbf{Q}^{-1}\mathbf{r}_A \rangle = 1 \iff \langle \mathbf{Q}^{-1}\mathbf{x}, \mathbf{r}_{\mathbf{Q}^{-1}(A)} \rangle = 1$$

³ $\mathbf{Q}^{-1}\mathbf{X}$ is elementary normally distributed, but it does not necessarily have a unit covariance matrix.

$$\iff \mathbf{Q}^{-1}\mathbf{x} \in \mathbf{Q}^{-1}(A).$$

Using our previous result, we find:

$$\begin{aligned}\tilde{\mathbf{x}}_A &= \mathbf{Q} \overbrace{(\mathbf{Q}^{-1}\mathbf{x})_{\mathbf{Q}^{-1}(A)}}^{} = \mathbf{Q} \left(\mathbf{Q}^{-1}\boldsymbol{\mu} + \frac{1 - \langle \mathbf{Q}^{-1}\boldsymbol{\mu}, \mathbf{Q}^{-1}\mathbf{r}_A \rangle}{\langle \Lambda \mathbf{Q}^{-1}\mathbf{r}_A, \mathbf{Q}^{-1}\mathbf{r}_A \rangle} \Lambda \mathbf{Q}^{-1}\mathbf{r}_A \right) \\ &= \boldsymbol{\mu} + \frac{1 - \langle \mathbf{Q}^{-1}\boldsymbol{\mu}, \mathbf{Q}^{-1}\mathbf{r}_A \rangle}{\langle \Lambda \mathbf{Q}^{-1}\mathbf{r}_A, \mathbf{Q}^{-1}\mathbf{r}_A \rangle} \mathbf{Q} \Lambda \mathbf{Q}^{-1}\mathbf{r}_A = \boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\mu}, \mathbf{r}_A \rangle}{\langle \mathbf{Q} \Lambda \mathbf{Q}^{-1}\mathbf{r}_A, \mathbf{r}_A \rangle} \mathbf{Q} \Lambda \mathbf{Q}^{-1}\mathbf{r}_A \\ &= \boldsymbol{\mu} + \frac{1 - \langle \boldsymbol{\mu}, \mathbf{r}_A \rangle}{\langle \Sigma \mathbf{r}_A, \mathbf{r}_A \rangle} \Sigma \mathbf{r}_A.\end{aligned}$$



When we replace the *plane* A by a *half-space* B in Theorem 1.4.12, there are two cases to consider. If $\boldsymbol{\mu} \in B$, then $\tilde{\mathbf{x}}_B = \boldsymbol{\mu}$, because the mode of \mathbf{X} is $\boldsymbol{\mu}$, which is contained in B .

In the non-trivial case of $\boldsymbol{\mu} \notin B$, we find that $\tilde{\mathbf{x}}_B = \tilde{\mathbf{x}}_A$, where $A := \partial B$ is the *boundary* of B , which is a plane, given by the same pillar: $\mathbf{r}_A = \mathbf{r}_B$. A geometrical argument is as follows: by reducing to the case of an elementary normally distributed \mathbf{X} with a unit covariance matrix, the mode is the point of B that minimises the distance to $\boldsymbol{\mu}$. Since $\boldsymbol{\mu} \notin B$, this point must lie on the boundary of B , i.e. $\tilde{\mathbf{x}}_B \in A$. Because A is a subset of B , we can proceed to compute $\tilde{\mathbf{x}}_A$, which is then necessarily the mode of $\mathbf{X} \mid B$.

For a half-plane B , we now have an explicit expression for $\tilde{\mathbf{x}}_B$, i.e. the *most likely value* of \mathbf{X} , given that $\mathbf{X} \in B$. What can we say about the *expected value* of $\mathbf{X} \mid B$? Geometrically, one can imagine that $\mathbb{E}[\mathbf{X} \mid \mathbf{X} \in B]$ lies close to $\tilde{\mathbf{x}}_B$, but ‘shifted inwards’, away from ∂B (in the direction of its pillar). We have not found a direct method to compute this expected value. Nesti et al. (2018a) introduce a scaling factor $\epsilon > 0$ to the covariance of \mathbf{X} (i.e. $\mathbf{X}_\epsilon \sim \mathcal{N}(\boldsymbol{\mu}, \epsilon \Sigma)$), and show that the expected value *converges* to $\tilde{\mathbf{x}}_B$, the mode,⁴ as $\epsilon \rightarrow 0$, using the tools of Large Deviations Theory.

One can interpret this result as saying that the probability density of $\mathbf{X}_\epsilon \mid B$ gets *concentrated close to the boundary of B* . In the one-dimensional case, this statement⁵ is easy to demonstrate, see e.g. ?.

Is de marginale verdeling gaussiaans verdeeld? (Ze is niet normaal verdeeld.) Wat is de covariantiematrix? Je zou als Stap 0 kunnen transformeren naar een \mathbf{r}_A die parallel aan een van de assen loopt, en dan dat coordinaat gelijk aan $\|\mathbf{r}_A\|$ stellen? Maar dan klopt de verwachtingswaarde niet meer?

⁴The factor ϵ disappears in (1.5).

⁵i.e. the *tail distribution* of $X \sim \mathcal{N}(0, \epsilon^2)$, given $X \geq 1$, becomes *steeper* as $\epsilon \rightarrow 0$.

Het zou mooier zijn om dit resultaat toe te passen op een algemene Gauss-verdeling, die niet per se normaal is. De marginale verdeling bestaat dan alleen niet altijd, namelijk wanneer $A \cap \text{Im}(\mathbf{X}) = \emptyset$. Als ze wel bestaat, dan gok ik dat het Gaussiaans is.

Het is nu niet toe te passen op line flows (want die zijn normaal, wel Gaussiaans), maar wel op de injectie. Wanneer je dan de meest likely injectie hebt, kan je afleiden wat de flow is. Dit komt overeen met elkaar?

De covariantiematrix van de flow is ook bijna singulair (numeriek gezien singulair), omdat de correlaties zo sterk zijn. Maar ik denk dat je kan argumenteren dat de kans op singulaire covariantiematrix 0 is, en dan kan de stelling dus wel worden toegepast. Numeriek is de bijna-singulariteit ook geen probleem (denk ik), omdat in de uiteindelijke uitdrukking de inverse van sigma niet voorkomt.

Chapter two

Graph theory

2.1 Graph

The power grid forms an interconnected *network* of transmission lines, which makes Graph Theory a logical choice for modelling it. In fact, most electrical systems are modelled using graphs. In Circuit Theory, *nodes* represent electrically equivalent points in a circuit, and individual components (resistors, voltage sources) can be seen as the lines of the network.¹ We will study the electrical properties of the transmission network in Chapter 5, but for now, we will simply accept that the transmission network consists of *nodes* and *lines*, and that the lines can transfer power between nodes in a straightforward (linear) way. Physically, the power flows are determined by the amount of power injected at each node, which in turn is determined by the devices that we connect to the transmission network. In this chapter, we will study the *converse*:

What does the flow of power tell us about the power injection at the nodes?

To do so, we will build upon the tools of Linear Algebra and Graph Theory, as covered in most elementary textbooks on these subjects.

We use, without proof:

undirected graph, subgraph, path, loop, euler path, connected, k-edge-connectivity, tree, minimum spanning tree

thm: every connected graph contains a minimum spanning tree

thm: G is a tree iff $m=n-1$

thm: removing a leaf from a tree results in a new tree

thm: eulerian path in a tree is unique

2.2 Directed graph

When studying the flow of current in a network, it is useful to fix a direction for each line, relative to which the flow can be expressed. Semantically, a *positive* flow along an edge will mean a flow in the same direction as the edge, while a *negative* flow describes a 'positive' flow in the opposite direction. The choice of line direction could be seen as

¹This simplification is only true for components with 2 terminals. A transistor has 3 terminals, for example.

When flow is complex-valued, there is no pos/neg.

arbitrary.

Definition 2.2.1. A *directed graph* is a pair $(\mathcal{N}, \mathcal{L})$ such that the set of *nodes* \mathcal{N} is finite, and the set of *lines* $\mathcal{L} \subseteq \mathcal{N} \times \mathcal{N}$ satisfies:

wikipedia
calls this
a 'Gain
Graph'

- If $(i, j) \in \mathcal{L}$, then $(j, i) \notin \mathcal{L}$. (i.e. there are no 'loops' between two nodes.)
- For each $i \in \mathcal{N}$: $(i, i) \notin \mathcal{L}$. (i.e. no node is directly connected to itself.)

2.3 Flow

For the remainder of this section, assume that $G = (\mathcal{N}, \mathcal{L})$ is a directed graph, where the nodes are labelled $\mathcal{N} = \{1, 2, \dots, n\} = [n]$ for some $n \in \mathbb{N}$.

The $m = \#\mathcal{L}$ lines of the network are labelled $\mathcal{L} = \{\mathcal{L}_1, \mathcal{L}_2, \dots, \mathcal{L}_m\}$.

Suppose \mathbb{K} is a field.

Definition 2.3.1. An *injection* is an element of \mathbb{K}^n .

Definition 2.3.2. A *flow* is an element of \mathbb{K}^m .

semantics

When $\mathbb{K} = \mathbb{F}_2$, a flow can be seen as a subset of the collection of lines \mathcal{L}

Definition 2.3.3. An injection $\mathbf{p} \in \mathbb{K}^n$ is *induced* by a flow $\mathbf{f} \in \mathbb{K}^m$ if:

$$p_i = \sum_{\mathcal{L}_k=(i,j) \in \mathcal{L}} f_k - \sum_{\mathcal{L}_k=(j,i) \in \mathcal{L}} f_k \quad (2.1)$$

for each node $i \in \mathcal{N}$. ($p_i = 0$ for isolated nodes.)

Note that \mathbf{p} is uniquely defined for every choice of \mathbf{f} . This allows us to define a function:

Definition 2.3.4. Suppose G has no isolated nodes. We define the *Flow Response Transformation* (K) as the function

$$K : \mathbb{K}^m \rightarrow \mathbb{K}^n$$

that maps a flow $\mathbf{f} \in \mathbb{K}^m$ to the unique injection $\mathbf{p} \in \mathbb{K}^n$ that it induces.

From (2.1), it follows that K is a linear map. In fact, when written in matrix form, we find a familiar result: K is the vertex-edge incidence matrix of G !

hier
definieren?

The fact that K is a linear map raises an interesting question: how can the image and kernel of K be interpreted in the context of digraph flows? The reader is invited to revisit Example to visualise these sets.

examples

One can interpret the image of K as the set of injections that can be redistributed along the network. Because a flow only serves to redistribute injections from one node to another, nothing is lost or gained in the network. This imposes the condition that an injection vector must have *zero sum*. Moreover, when G is connected, *all* zero sum injections can be induced by a flow.

The kernel can be interpreted as the set of all flows that result in zero injections. Besides the trivial case of zero flow, any constant flow along a closed loop induces zero injection. We will find that these *loop flows* generate *all* flows in the kernel of \mathbf{K} .

When G is a planar graph, loops around the faces of G actually form a *basis* for the kernel. In the more general case that G is connected, but not necessarily planar, such a basis can also be constructed by fixing a *minimum spanning tree* of G .

As an added bonus, applying the Rank-Nullity theorem to \mathbf{K} when G is planar provides us with an alternative proof of Euler's Formula.

These statements will be made more precise in the next sections, when we study the image and kernel of \mathbf{K} in more detail.

2.3.1 Image of \mathbf{K}

intro

Definition 2.3.5. The function $\sigma : \mathbb{K}^n \rightarrow \mathbb{K}$ defined by

$$\sigma : \mathbf{p} \mapsto \sum_{i=1}^n p_i$$

is the linear map from an injection vector \mathbf{p} to the *net injection* of \mathbf{p} .

The kernel of σ is the set of zero-sum injections:

$$\ker \sigma = \left\{ \mathbf{p} \in \mathbb{K}^n \mid \sum_{i=1}^n p_i = 0 \right\}.$$

When G is connected, this is exactly the set of injections that can be induced by a flow on G :

Theorem 2.3.6. Suppose that G is connected. Then

$$\text{Im } \mathbf{K} = \left\{ \mathbf{p} \in \mathbb{K}^n \mid \sum_{i=1}^n p_i = 0 \right\} \cong \mathbb{K}^{n-1} \quad (2.2)$$

We will prove this equality by considering the two inclusions \subseteq and \supseteq separately. The first inclusion follows from the observation that \mathbf{K} is the vertex-edge incidence matrix of G .

Lemma 2.3.7. Suppose that G is connected.

$$\text{Im } \mathbf{K} \subseteq \ker \sigma \quad (2.3)$$

Proof. We write $\mathbf{e}^1, \dots, \mathbf{e}^m$ for the standard basis of \mathbb{K}^m .

Since \mathbf{K} is linear, one only needs to verify that $\mathbf{K}(\mathbf{f}) \in \ker \sigma$ for each $\mathbf{f} = \mathbf{e}^k$ in the basis. The vectors $\mathbf{K}(\mathbf{e}^1), \dots, \mathbf{K}(\mathbf{e}^m)$ are exactly the columns of the matrix \mathbf{K} , which all have zero sum: a column corresponds to a line in G , and has exactly two non-zero entries: 1 for the entering node, and -1 for the leaving node. 

To prove the inclusion \supseteq implied by Theorem 2.3.6, we first consider the special case that G is a *tree*.

Lemma 2.3.8. *Suppose that G is a (connected) tree.*

$$\text{Im } K \supseteq \ker \sigma \quad (2.4)$$

Proof. G is a tree, so $m = n - 1$. Because \mathbb{K}^m and $\ker \sigma$ both have dimension $n - 1$, we only need to prove that K is injective: when K has nullity 0, it must have rank $n - 1$.

If $n = 1$, then the digraph consists of a single node, and no lines. It then follows from (2.1) that the only injection that can be induced is $\mathbf{p} = (0) \in \mathbb{K}^1$, so K can only be injective.

If $n > 1$, we will use the fact that the statement holds for any tree with fewer than n nodes. (*Proof by induction.*)

Suppose that $f \in \mathbb{K}^m$, such that $\mathbf{p} = K(f) = \mathbf{0}$. Because G is a tree, we can² pick a leaf $i \in \mathcal{N}$, which has a unique line \mathcal{L}_k connecting i to some $j \in \mathcal{N}$. (We have either $\mathcal{L}_k = (i, j)$ or $\mathcal{L}_k = (j, i)$.)

Only one line is connected to i , so (2.1) gives: $p_i = \pm f_k$. (The sign depends on the orientation of \mathcal{L}_k .) We assumed $p_i = 0$, so we must have $f_k = 0$.

By removing node i and line \mathcal{L}_k , we obtain a smaller tree, for which the statement already holds. The Flow Response Transformation of this subtree is essentially the restriction of K to the set $\{f \in \mathbb{K}^m \mid f_k = 0\}$. Because the restriction is injective, all other coefficients of \mathbf{p} are also zero. This shows that K is injective, and the result follows. 

Proof of Theorem 2.3.6. To prove $\text{Im } K = \ker \sigma$, it remains to show that

$$\text{Im } K \supseteq \ker \sigma \quad (2.5)$$

holds for *any* connected G , not just for trees.

Since G is connected, we can choose a minimum spanning tree: choose $T \subseteq [m]$ with $\#T = n - 1$ such that $G_T = (\mathcal{N}, \{\mathcal{L}_k\}_{k \in T})$ is such a connected subdigraph.

Define $F_T = \text{Span}\{\mathbf{e}^k\}_{k \in T} \subseteq \mathbb{K}^m$ as the subset of flows on G that are zero outside of G_T . Because F_T is a linear subspace of \mathbb{K}^m , we have

$$\text{Im } K = K(\mathbb{K}^m) \supseteq K(F_T),$$

which reduces the problem to $K(F_T) \supseteq \ker \sigma$, which follows from Lemma 2.3.8.

This shows that

$$\text{Im } K = \ker \sigma.$$

Because $\sigma : \mathbb{K}^n \rightarrow \mathbb{K}$ is surjective, it has rank 1. It therefore has nullity $n - 1$, or equivalently, $\ker \sigma \cong \mathbb{K}^{n-1}$. 

²Write $\text{gr}(i)$ for the number of lines connected to i . G is connected, so $\text{gr}(i) \geq 1$ for each $i \in \mathcal{N}$. If no i exists with $\text{gr}(i) = 1$, then $\text{gr}(i) \geq 2$ for each $i \in \mathcal{N}$, giving $\sum_{i=1}^n \text{gr}(i) \geq 2n$. On the other hand, each of the $n - 1$ lines connects exactly two nodes, so $\sum_{i=1}^n \text{gr}(i) = 2(n - 1) < 2n$, a contradiction.

This proof could benefit from an illustration.

A single-node graph is not connected?

Make this mapping explicit?
The fact that $p_i = 0$ is required?

Is this clear enough?

2.3.2 Kernel of K

Again, assume that G is connected. In Theorem 2.3.6, we derived an explicit formulation for the image of K , showing that $\text{null } K = n - 1$.

Concerning the kernel of K , we already know that $\mathbf{0} \in \ker K$, reflecting the fact that zero flow induces zero injection. In the special case that G is a tree, this is the only such flow. In general, however, the kernel of K is much bigger.

introduce loops

Proposition 2.3.9. Suppose that G is connected. The dimension of $\ker K$ equals

$$\text{null } K = m - (n - 1).$$

Proof. This follows directly from the Rank-Nullity theorem, applied to Theorem 2.3.6. state



Corollary 2.3.9.1. If G is a tree, then $\ker K = \{\mathbf{0}\}$, and K is a bijection between \mathbb{K}^m and $\ker \sigma$.

Proof. Applying Proposition 2.3.9 with $m = n - 1$, we find that $\text{null } K = 0$, so that $\ker K = \{\mathbf{0}\}$. Together with Theorem 2.3.6, we find the result. proof

talk about loops, use an example graph

Any flow along a *closed loop* results in zero power injection. When interpreting a loop as an element \mathbf{f} of \mathbb{K}^m , we must be careful to *flip the sign of f_k if the line L_k is traversed in reverse*.

Theorem 2.3.10. Suppose that G is connected and that (i_1, i_2, \dots, i_p) is a closed Eulerian loop. Then the loop flow $\mathbf{f} \in \mathbb{K}^m$ defined by:

$$f_k = \begin{cases} 1 & \text{if } (i_s, i_{s+1}) = L_k \text{ for any } 1 \leq s < p, \\ -1 & \text{if } (i_{s+1}, i_s) = L_k \text{ for any } 1 \leq s < p, \\ 0 & \text{otherwise,} \end{cases} \quad (2.6)$$

for each line L_k , is an element of the kernel of K .

Proof. We will verify that $\mathbf{p} = K(\mathbf{f})$ is zero. Choose any $i \in N$.

this thm
only works
for Eulerian
paths...

Because the loop is closed, there is an *even* number (possibly zero) of lines with non-zero flow that connect to i . This means that the sums in (2.1) cancel each other (note the negative sign for reversed lines in (2.6)), resulting in $p_i = 0$. proof

Remark. Because K is linear, multiplying a loop flow with a scalar $\gamma \in \mathbb{K}$, or adding two loop flows, creates a new flow that induces zero injection. (The result of addition is a flow, but in general not a *loop* flow.)

Now that we know the dimension of $\ker K$, a natural next step is to look for a *basis* that generates the kernel. Motivated by the previous theorem, we will look for a basis consisting of *loop flows*.

When looking at the previous examples, a logical choice for this basis would be the set of all flows in *loops surrounding the faces contained in the graph*. This approach, which only works for *planar graphs*, will be discussed in the next section.

For now, we would like to find a basis of loop flows for the more general case that G is connected, but not necessarily planar. We proceed as follows:

Definition 2.3.11. Suppose that G is connected, and that $T \subseteq [m]$ is a minimum spanning tree. For each remaining line $\mathcal{L}_k = (i, j) \in \{\mathcal{L}_k \in \mathcal{L} \mid k \notin T\}$, there exists a *unique Eulerian path along the tree* from j to i , say

$$(i_1, i_2, \dots, i_p), \quad \text{where } i_1 = j \text{ and } i_p = i.$$

By adding the chosen line \mathcal{L}_k to this path, we find a closed Eulerian loop in G : $(i_1, i_2, \dots, i_p, j)$, which defines a loop flow \mathbf{f}^k .

We define the *spider web basis on T* as the set of loop flows defined this way: $\{\mathbf{f}^k\}_{k \in [m] \setminus T}$. (If T were to represent a physical tree, a spider could spin a web from i to j by attaching a strand to j and then walking the Eulerian path to i .³)

Theorem 2.3.12. *The spider web basis on T constructed in Definition 2.3.11 is a basis for $\ker K$.*

Proof. Because T is a minimum spanning tree, it has $n - 1$ elements, and so the spider web basis consists of $m - (n - 1)$ loop flows. Because the number of elements in the basis equals the dimension of $\ker K$, one only needs to prove that they are linearly independent. Indeed, for each $k \in [m] \setminus T$, the loop flow \mathbf{f}^k is the only element for which the k^{th} entry is non-zero. Therefore, \mathbf{f}^k cannot be written as linear combination of the other fundamental loops. 

In het geval $\mathbb{K} = \mathbb{F}_2$ (het lichaam van 2 elementen) heet dit de fundamentele groep van de graaf.

2.3.3 Planar Graphs

The spider web basis can be constructed for any connected graph. When the graph is also *planar*, a more intuitive basis exists. Without providing a rigorous definition, we simply say that a graph is *planar* if it can be ‘drawn on a piece of paper without any crossing lines’. Such a drawing creates *faces*: areas enclosed by lines.⁴ Different drawings can produce different collections of faces.

If we fix a collection of faces for a planar graph, then each face is enclosed by some of the lines, which form an Eulerian loop in the graph. We define the *planar basis on this drawing* as the set of loop flows defined by those Eulerian loops: each face becomes an element in the basis.

³It turns out that this is not how most spiders cover large distances: instead, they produce a long thread, and let it drift in the wind until it sticks to another surface. Clever!

⁴We do not consider the infinite enclosing area as a ‘face’.

th: in a planar embedding of a planar graph, the loops surrounding faces form a basis. proof: (in F2):

linearly independent: these loops are all loops with the property that exactly one face is contained in the loop.

complete: start with a spider web basis. choose a loop f in the spider web basis. this loop f contains a number of faces. f is equal to the sum of the loops around these faces. this shows that f can be written as linear combination of planar loops.
QED

Corollary 2.3.12.1 (Euler's Formula). *In a planar, connected graph, we have:*

$$v + f - e = 1$$

where v is the number of vertices, e is the number of edges, and f is the number of faces enclosed by edges, excluding the 'exterior face'.

Grid connected iff admittance matrix has full rank? or M?

Chapter three

Circuit Theory

3.1 *DC Circuits

A short summary of KCL, KVL, Ohm's Law, the Superposition principle, lumped circuits

3.1.1 *Derivation of KVL& KCL from Maxwell's eq

See von
Meier (2006)
and Slepian
(1968)

applying Maxwell's equations to the discrete graph topology

3.2 AC Circuits

Impedance, real & reactive power

Chapter four

The Electric Grid

(100W = 16-candela = 200lm = 2.2Watt bij ikea)

30%? of energy use is transported using the grid

list of synchronous grids

complexity

why interconnect? separate generation and load; economy of scale; security (distributed peak demand); stability;

This chapter is based on the books Electric Power Systems by von Meier (2006), which provides a clear summary of the working and operation of electric grids, and Electric Power Principles: Sources, Conversion, Distribution and Use by Kirtley (2010), a more quantitative approach to the subject.

4.1 Overview

One could say that the electric grids of this word are some of the largest machines built by humans.

As this system was built by clever engineers, its behaviour is, on a small scale (individual lines, transformers, and so on) *well-understood*. In fact, one of the reasons that all transmission lines, substations and switchboxes look so similar, is to increase the *homogeneity* of the network.

On a larger scale, however, the behaviour of this machine is not always well understood, as complex behaviour.

Because of their scale and complexity

basics, scale, transmission-distribution-?, europe-US, security

4.2 Generators

Almost all sources of electric power in the electric grid use an *AC generator* to convert (rotational) kinetic energy to electric energy.¹ At a hydroelectric plant, the weight of water applies direct torque to the water pumps, mechanically connected to the generator shaft.² At most other types of plants (including coal-fired and nuclear plants), generators are powered by steam pressure.

The term *AC generator* denotes a specific device that uses *electromagnetic induction* to convert rotational kinetic energy into AC power. Somewhat confusingly, we use the term *generator* to denote *any* energy source connected to the grid, where we consider a power plant (which might house multiple AC generators) as a single generator. Solar parks and lithium batteries are generators, but they do not use an AC generator. They use an AC inverter, which *mimics*, to some extent, the behaviour of a classical AC generator.

coils, 3 phase

4.3 Loads

load profiling, load series, fridge duty cycle example, reactive load, power factor

Unlike other utilities like gas and water, the transfer of electrical energy is *instantaneous*.³ Of course, energy storage does exist,⁴ but this energy is not stored as ‘high-voltage AC energy’, but as *potential* (mechanical or chemical) energy. Potential energy needs to be converted before it can be transmitted, which is not instantaneous. When switching on your lights, there will be an *instant* increase in demand, which must be generated somewhere (otherwise it would violate the Law of Conservation of Energy). Of course, via the electric grid, your light bulb is connected to generators, which then start converting an additional 10 W to power the light bulb. But how do the generators know when to increase their output, if you never called them to say that you are turning on your lights?

The answer is called *electric inertia*. A classic AC generator (in a hydroelectric plant, for example) contains a heavy rotor, which is spinning at (a rational fraction of) the grid frequency. Because of its weight, a lot of energy is stored in the spinning of the rotor. When the total load on an AC network is increased, there is no instantaneous

¹A notable exception is the photovoltaic cell (PV cell) used in solar panels. PV cells produce a direct current, which is converted to AC power at nominal voltage using an *inverter*. Solar inverters are often complicated systems, capable of using battery storage, synchronising with the AC grid and varying PV operating voltage to maximise PV efficiency.

²Some hydroelectric plants are *reversible*: their generators can be used as electric motors, pumping water back up into a reservoir. This is a form of large-scale *energy storage*, which can increase the usability of intermittent renewable energy sources.

³Within the limits of special relativity, of course. That is, while the drift speed electrons is nowhere near the speed of light, the actual *signal* propagates at about two thirds the speed of light, depending on the type of cable.

⁴Most commonly as *reversible* hydro-electric generators; other examples include hydrogen storage (electrolysis of water produces hydrogen and oxygen, which can be stored and combusted at a later time) and lithium storage (very large phone batteries) (some electric vehicles can also return energy back to grid!)

increase in burning of fuel, flowing of water, or otherwise. Instead, this increase in power demand will ‘take’ its energy from the *inertial energy* of all rotational AC generators in the grid, *slowing down* their rotation. As a result, the AC frequency of the entire grid starts slowing down. When grid operators notice a drop in AC frequency (we are talking about differences on the order of 0.001 Hz here), they can increase the amount of fuel being burned, open water valves or lift control rods from between radioactive cores to increase the amount of energy converted by the AC generator. This will start to increase the AC frequency again, until it settles at the predetermined utility frequency (60 Hz in North America and Northern South America; 50 Hz in the rest of the world, with some exceptions). Most modern AC generators have an automatic feedback loop to control the steam valve, to allow for frequency adjustments on the smallest scale.

4.4 Transmission

Should cover: lines, transformers, circuit breakers, grid security

4.4.1 DC transmission

4.4.2 3-phase transmission

The AC grid has 3 phases, but it is very common to model the grid as a single-line network (with a global, zero-impedance ground). Von Meier mentions material that justifies this change.

If you live in mainland Europe, North America, , your wall socket will have two connectors. Most modern sockets also have a third connector, the *ground wire*.

This makes sense, since most electrical devices only need a *potential difference* (between *two wires*) to function. In the early days of transmission systems, however, this caused a problem for factories using AC motors to power their production line. When a (single-phase) AC current is used to power a motor, the amount of *torque*⁵ is not constant: when the potential difference is zero, which happens twice every 1/50th of a second, no electric field is present in the armature windings, and no torque is applied to the rotor.

To solve this problem, both the AC generator and AC motor are equipped with *three* identical sets of armature windings, each oriented 120° relative to the others. One end of each winding is connected to the common ground, and the remaining three connection points form the *three-phase connection* between generator and motor.

en waarom
is dat een
probleem?

As the generator rotor is moving, there will always be one armature winding which is close⁶ to being perpendicular to the rotor windings, and will therefore have a relatively high induced current.

⁵i.e. rotational force. In most systems, torque is proportional to *change in rotational velocity* (change in rpm).

⁶within 30°

In fact, when writing down the three currents in exact form (three sinusoids with the same frequency and magnitude, with phases 0° , 120° and 240°), we find that *the sum of their squares*, i.e. the total amount of transmitted power, *is constant!* Although the amount of power transmitted on just one of the phases (square of the sinusoid current) is not constant, the combination of the three is.

This means that the torque of a motor, which is the sum of torques applied by each armature winding, is constant.

Nu weten we ook wat het verschil is tussen ground en de linkerdraad!

What we just described is a *Wye connection* om ons heen

When looking at AC transmission systems, you will always find three identical copies of the same component. For example, high-voltage AC transmission lines always have three, six or nine wires, which are identical in material, thickness and length.

There are a number of reasons to build transmission systems this way. One benefit of having three copies of the exact same network is that they will behave the same way, saving grid operators up to two thirds of potential headaches!

Single-line approximation

Move to next 5?

4.4.3 Line failures

When a transmission line stops transmitting power, we speak of a *line failure*. In most cases, a line failure is not caused by a broken or molten wire, but by a disconnection at one of its ends, as a safety measure. Some line failures are caused by a fault: a sudden abnormal peak in current, caused by anomalies like fallen trees or lightning strikes. A high current is detected by a *circuit breakers*, which then automatically breaks its connection. A household fuse is an example of a circuit breaker, although modern circuit breakers use a mechanical switch (which can be reset, instead of requiring a replacement fuse). In high-voltage systems, circuit breakers can be quite advanced, sometimes using pressurised gas or oil to prevent arcing inside the switch.

Another type of line failure, the one most relevant to this report, is an *overload*. All transmission lines have a *thermal limit*: a maximum current that the line can sustain without risking overheating, causing sagging or even melting of transmission cables. To prevent these dangerous scenarios, transmission lines automatically disconnect when the current exceeds the predetermined *line capacity*.

or stability limit

It is important to note that grid operators cannot control the amount of current - and therefore - power that flows through a transmission line, grid operators can only connect or disconnect the line from the grid. The impedance of a wire does not act as a *bottleneck* (like a small-diameter pipe would do in an irrigation network). From Ohm's law ($ZI = V$), one could mistakenly conclude that the amount of current passing through a transmission line is inversely proportional to its resistance. However, the electric potential (V) in this equation is *not* the potential between the wire and the ground (e.g. 220 kV), but rather the potential difference between the two ends of the wire (which is not zero!). This difference (known as *line drop*) is quite low, compared to the potential between one of the ends and the ground (220 kV transmission lines usually have a 1% line drop). The amount of current carried by a wire is dominated by

check

the current being 'generated' and 'used' at its ends.

not the case for DC transmission?

4.5 Power Flow Analysis

historic note, slack bus, distributive slack, DC approximation, optimal power flow

4.6 Transmission grid operation

The transmission network is a crucial

The transmis

In societies that

Historically, failures of transmission network have had dramatic effects. The effects of such outages are even visible from space, since almost every light source indirectly depends on a functioning transmission network.

Luckily, TODO where a power-outage would be life-threatening, or has significant economic impact, often have backup generators in place.

In modern hospitals, medical equipment often has a built-in battery to sustain relatively short power cuts. (When unplugged by accident, for example.) Hospitals also use two sets of power lines with independent protection: one for essential equipment, and one for computers, lights, phone chargers, et cetera.

It should come as no surprise that the transmission network requires constant monitoring to ensure that it is working properly.

When the first power grids were built, grid security was ensured by *redundancy*. Transmission lines were designed to carry currents much greater than predicted. One of the criteria for building a network was *N-1 contingency*: the network should remain operational after the failure of *any* line. In graph theory, this is equivalent to building a 2-edge-connected graph.

historic note

4.6.1 Power islanding

Because nodes often house both loads and generators, the disconnection of a single node, or of a subset of nodes, does not always lead to a power outage, since local power generation might be sufficient to serve the load. This situation, where a subsection of the transmission network still operates after being disconnected, is called a *power island*.

Since the power island and the remaining network have been operating independently of each other, it is likely that their AC phase angles no longer line up.⁷ Unless this phase drift is corrected for (by temporarily increasing or decreasing the AC frequency

⁷This misalignment likely occurs right after the disconnection, when the total generation in the power island is substantially higher or lower than the total load. Until this mismatch has settled, the AC frequency will be higher or lower, respectively, than the target frequency (say, 50 Hz).

on either side), the power island cannot be reconnected, since this phase drift likely exceeds the power angle limit of a new transmission line.

adsf

4.6.2 The energy market

Modern power grids play the role of a competitive economic market. There are many possible ways to supply everyone with power, because there is more *installed capacity* than there is demand. As a result, generation shares are largely determined by *bidding*. Different generation technologies (gas, wind, etc.) form a *stacking order*: in general, wind energy will always be cheaper than coal. Yet, it is not uncommon for renewable, cheap energy sources to be *curtailed*, in favour of more expensive, possibly non-renewable energy sources. One of the reasons for grid operators to do so, is to protect vulnerable lines from overloading.

In this section, we will describe a very simplified version of the energy market, to illustrate how grid operators ensure grid security while minimising costs.

Every hour, all parties involved in the generation and transmission of power come together, to decide *what the configuration during the following hour will be*. For the sake of simplicity, we will assume that each power plant (renewable or non-renewable) is owned by its own company, and that the entire transmission network is owned by a single grid operator.

Phase one: offering prices

First, all generators offer to supply energy during the coming hour *for a certain price per kWh*. Generally, company A, which owns a wind farm, will offer their energy for a lower price than company B, which owns a coal plant. The price offered by company A is lower because a wind farm has zero *marginal cost* - the cost of generating an additional unit of electricity, once the turbine has been built. No fuel or labour is needed to generate power using a wind turbine, it simply needs to not be turned off.

Besides marginal cost, there are two more factors that influence the offered price:

- Company A needs to pay back their initial investment, which increases the offered price.
- Government subsidies, which promote the use of low-carbon energy, reduce the offered price.

In general, one can assume that the price offered for renewable energy is close to zero. In some cases, the subsidies are greater than all other costs, and energy is offered for a *negative price*. This has the counter-intuitive effect that a grid operator actually *earns money* by buying electricity from that company.

Energy from company B is generally more expensive, since it has a marginal cost (price of coal, labour wages, and so on), on top of paying back the investment.⁸

Misschien is dit een goede plek om de *environmental cost* van elk type generator te geven

⁸In some cases, coal plants offer their electricity for a lower, or even negative, price, to avoid power off the plant. With the exception of open-cycle gas turbines, turning on non-renewable energy plants is expensive, and might take several hours. It might be cheaper for company B to offer their energy for free for one hour than to turn off the plant.

15 March 2019, 11:00-12:00		
generator	offered price	requested output
Sally's Solar Park	4 €/MWh	115 MW / 115 MW
Chris's Coal Plant	122 €/MWh	0 MW / 240 MW
Nellie's Nuclear Plant	45 €/MWh	1387 MW / 2500 MW
Steven's Solar Park	-2 €/MWh	23 MW / 23 MW
:	:	:

Table 4.1: A small section of a fictional configuration.

Besides offering their marginal price, generators will also state their *generation capacity*.⁹ For some generators, this will always be the same amount. For a solar park, however, this capacity varies drastically, and needs to be estimated.

Phase two: grid operator

Now that all generators have offered a price, the grid operator needs to decide where to buy its energy from. Grid operators have a fairly good estimate for the load (energy demand) during the coming hour, based on the current load, historical load series, weather forecasts, sporting events, television programme schedules, and so on. Such a model is called a *load profile*.

By design, the total generation capacity is much greater than the expected load, so running every generator at full capacity would be problematic. As a grid operator, we need to tell each generator at what percentage of their capacity they should operate.

A complete set of generator instructions, called a *configuration*, might look something like Table 4.1. Note that generators could be told to operate at 0% of their capacity, which is equivalent to powering off the generator completely.

Some configurations are more expensive than others, and some will result in more greenhouse gas emissions than others. Perhaps surprisingly, most configurations are not even *admissible*: using them would cause some transmission lines to be overloaded, which could even result in a blackout.

More precisely, a configuration is called *ready to deploy* if it satisfies the following three conditions:

possible: For each generator, the power output dictated by a configuration must be a non-negative number, no greater than the maximum capacity of the generator.

balanced: When the dictated configuration is applied, total generation must equal total load, together with line losses.¹⁰

load profile
plotje

why? winter
and incident
load

stats: het
percentage
van totale
capaciteit
dat wordt
gebruikt ligt
tussen ?%
en ?%.

admissible
is niet ja of
nee

⁹This use of the word *capacity* is entirely different from the *capacity* of a capacitor, used in electrical engineering.

¹⁰Of course, the total load is not perfectly constant for one hour. To accommodate for this, the grid operator designates a single *load following* generator, which will vary its output continually to make

admissible: When the dictated configuration is applied, no line should be overloaded.

To determine whether a configuration is *admissible*, the grid operator can simply *calculate the line flows* that would be induced by that configuration, using a Power Flow (PF) algorithm, and check for any overloaded lines. Because power flow physics are quite well-understood, these results are accurate.

accuracy

geschiedenis
van PF:
modellen

OPF

We can easily find a configuration that is both possible and balanced. First, set all generators to maximum capacity. We now have a *possible* configuration. By design, the total generation of this configuration is much greater than the total load. By scaling the output of all generators with the same factor $0 \leq \lambda \leq 1$, the configuration remains *possible*, and by the intermediate value theorem, a λ exists such that the configuration is *balanced*.

When trying out different *possible*, *balanced* configurations randomly, we will find that almost all of them are inadmissible; the subset of admissible configurations is actually quite small, and finding *any* ready-to-deploy configuration is a lot of work.

Once a ready-to-deploy configuration has been found, the grid operator now wants to minimise economic and environmental cost. Given this initial configuration, the associated cost can be calculated, since all generators have offered their price, and their environmental impacts are known. This ready-to-deploy configuration is not unique, and by varying the configuration only slightly, the configuration remains ready to deploy.¹¹ By doing so, we might be able to reduce the (environmental) cost! By repeating this process, a local minimum can be found.

The problem of

*finding a ready-to-deploy configuration
that minimises the associated cost*

is called the *Optimum Power Flow (OPF)* problem.

Even with modern-day computers, solving this problem is a difficult task indeed, and is often simplified by making a slight modification to our process. Instead of using the Power Flow (PF) algorithm to check a configuration's admissibility, we use the so-called *Linearised Power Flow (LPF)* algorithm to check linear admissibility. This linearised version can be computed much more quickly, with only a small loss in accuracy. We will derive the equations describing these two algorithms in Chapter 5, and compare their results.

linear bal-
ance

sure that the total demand is met exactly. (This is equivalent to maintaining a constant AC frequency!) The bus that this generator is connected to is called the *slack bus* of the transmission network.

¹¹As we will later learn, the function that maps a configuration to the vector of line flows that it induces is *continuous*. The set of vectors where each line flow is < 100% is an *open* box, and so its inverse image (the set of configurations that are ready to deploy) is also open.

With our slight modification, we restate our problem as:

minimise *associated cost*
subject to *possibility*
and *balance*
and *linear admissibility*

which is known as the *Linear Optimum Power Flow (LOPF)* problem. As suggested by the notation, this optimisation problem falls in the more general class of problems solvable using *linear programming*. First studied by Fourier in 1827, the field has seen many developments, most notably the *simplex* solution method developed by G. Dantzig in 1947.¹² Nowadays, several high-performance linear programming solvers have been created, including the open source GNU Linear Programming Kit, which was used in this project.

Je kan de eisen van OPF naar beneden schalen om lineaire admissibility te krijgen (bv de contingency factor!)

¹²For the *simplex method*, see Matoušek and Gärtner (2007) .

Chapter five

Modelling Transmission Networks

In this Chapter we will derive the *Linear Power Flow* (LPF) transformation: a linear map from the vector of power injections at the buses to the vector of currents flowing through the lines of the network.

It is a *right inverse* of K , which means that applying LPF to a power injection gives a flow that would induce that injection. There are many possible candidates for a right inverse. One way to construct one is to fix a minimum spanning tree. When we set line currents outside of the tree to zero, all line currents inside the tree are uniquely determined.

Yet, only one right inverse is *physically correct*: the LPF. This function can be derived explicitly by constructing an electric circuit that represents the whole transmission network and everything connected to it, and applying Ohm's Law and Kirchoff's Laws to relate line currents to power injections. We linearise the resulting *node flow equations* to find the LPF matrix (page 46).

Using this linear map, we can transform the normal distribution of stochastic injections to a Gaussian distribution of line flows. Using the results of Chapter ??, we can estimate the overload probability of each line, resulting in a ranking of most vulnerable lines. Additionally, for each such line, we compute the most probable injection to cause the failure, and simulate the subsequent *cascading failures*.

5.1 The model

The LPF is essentially the *high-level model* used in the final chapters of this thesis (i.e. the transmission network is modelled as a linear transformation). In this chapter, we derive a closed-form expression for the LPF from a lower-level, *electrical* model.

5.1.1 Electrical model

We make a distinction between the *structure* and the *state* of the network. The structure is a directed graph, where each line is given an *admittance*. The state collects the (real and reactive) power injected at each bus, the (complex) voltage of each bus, and the (complex) current flowing through each line.

The use of complex-valued voltage and current (and therefore power) is essential when analysing AC circuits, even though we are only interested in *real* power. For example, we will find that the amount of real power transmitted over a line is approximately inversely proportional to the inductance of the line (the *imaginary* equivalent of resistance), and approximately proportional to the difference in phase angles at its ends (the *complex argument* of voltage).

5.1.2 Time invariance

The grid structure remains unchanged during normal operation, while the grid state is continually changing over time. For example, an important aspect of grid operation is *load profiling*: examining and predicting the total load connected to a node, as a function of time. As a result of changing loads, the flow of power in a grid is constantly changing.

One example of a change in grid structure is a *line failure*, which can be modelled as the removal of an edge from the graph. In some cases, the removal of an edge from the graph result in an unconnected graph (i.e. there exist two nodes with no sequence of lines connecting them). This scenario is called *power islanding*. Most transmission networks are designed in such a way that no single (or double) line failure can cause power islanding or a blackout, by increasing the *edge-connectivity* of the graph.

In the case of a *line overload*, however, a line failure is caused by an exceptionally high power flow, as a result of high supply or demand.¹ The failure of an overloaded line will cause a redistribution of power flow, since the power flowing through the failed line now needs to 'find another path' between the nodes. In a highly stressed network, this redistribution can cause a second failure, which can then cause a third failure, and so on, eventually causing a blackout. We will study these *cascading failures* in Section 6.6.

5.2 Grid structure

A transmission grid is modelled as a directed graph $(\mathcal{N}, \mathcal{L})$. As vertices we take the *nodes* of the network, which are those points where transmission lines connect to a generator, load, or to each other. Nodes are electrically distinct, in the sense that there is some non-zero impedance between them, allowing them to sustain a potential difference. In a network of n nodes, they are represented by the natural numbers $1, \dots, n$, i.e. $\mathcal{N} = [n]$.

A pair of two distinct nodes (i, j) is contained in our set of lines \mathcal{L} if there is a transmission line connecting the nodes. The choice of line orientation can be arbitrary, but we fix the orientation to $i < j$, i.e. $(j, i) \notin \mathcal{L}$. This transmission line has non-zero impedance. (Otherwise i and j would be the same node.) In a network of m lines, lines are labelled $\mathcal{L}_1, \dots, \mathcal{L}_m$.

In literature on the subject, *buses*² are also called *vertices* or *nodes*, and lines can be

We model the line protection mechanism as deterministic: overload causes instantaneous failure.

Require the graph to be connected? How about power islands?

and in this thesis, oopsie

¹These high power injections are not necessarily located at the two endpoints of an overloaded line; it could also be a grid-wide pattern of power injections, all adding up to a high power flow on that line. We will study the *most likely power injection* in Chapter ??.

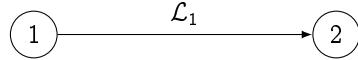


Figure 5.1: The simple *two-node* transmission network of two nodes and one line.

called *edges*, *wires*, *cables* or *circuits*.

Given a directed graph with n buses and m lines, we define the vertex-edge incidence matrix $\mathbf{K} \in \mathbb{R}^{n \times m}$ as:

$$K_{i,k} = \begin{cases} 1 & \text{if } \mathcal{L}_k = (i, j) \text{ for some } j \in [n], \\ -1 & \text{if } \mathcal{L}_k = (j, i) \text{ for some } j \in [n], \\ 0 & \text{otherwise.} \end{cases}$$

The ordered set of lines is uniquely defined by the vertex-edge incidence matrix.

transmormer normalisation

We model transmission lines as time-invariant impedances, which are assumed to be constant under any electric potential and current, allowing us to apply Ohm's Law. Instead of the impedance Z of a line, we use its *admittance* $Y = 1/Z \in \mathbb{C}$,³ and Ohm's Law becomes:

$$I = VY$$

This allows us to define the admittance between two unconnected nodes as 0. (i.e. no current is induced by a potential difference.) We define $\eta \in \mathbb{C}^m$ as the *admittance vector*, where η_l is the admittance of \mathcal{L}_l , for each $l \in [m]$.

Definition 5.2.1. To summarise, an (n, m) -grid structure is defined as a tuple $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \eta)$, where:

- $n = \#\mathcal{N}$ is the number of nodes;
- $m = \#\mathcal{L}$ is the number of lines;
- $(\mathcal{N}, \mathcal{L})$ is a connected directed graph with $\mathcal{N} = [n]$;
- $\mathbf{K} \in \mathbb{R}^{n \times m}$ is the vertex-edge incidence matrix of $(\mathcal{N}, \mathcal{L})$;
- $\eta \in \mathbb{C}^m$ is the line admittance vector.

Example 5.2.2 (Two-node network). A very simple transmission network is one with just two nodes, and a single line connecting them. This *two-node network* is drawn in Figure 5.1. Although real networks are much bigger, this example is useful to illustrate some of the concepts introduced in this chapter.

²'bus' is short for 'busbar': the latin 'omnibus' in conjunction with 'bar': some high-voltage cables are connected by welding them to a heavy metal bar.

³Written in Cartesian form, $Y = G + iB$, where G is the conductance, and B the susceptance of a line. Both have unit siemens (S), or mho (the reverse of 'ohm'), defined as $1S = 1\Omega^{-1}$.

We have:

$$\mathcal{N} = \{1, 2\} \text{ and} \\ \mathcal{L} = \{\mathcal{L}_1\} \text{ with } \mathcal{L}_1 = (1, 2).$$

Since $n = 2$ and $m = 1$, \mathbf{K} is a 2×1 matrix:

$$\mathbf{K} = \begin{pmatrix} 1 \\ -1 \end{pmatrix}.$$

□

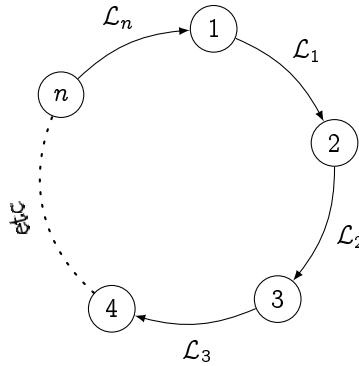


Figure 5.2: The n -loop transmission network with n nodes and n lines.

Example 5.2.3 (Loop network). A less trivial transmission network is the n -loop network, shown in Figure 5.2. It consists of n nodes, connected in a circular fashion (using n lines).

Note that this network is 2-edge connected, meaning that the network remains connected when any edge is removed. (Although removing *any* two lines will disconnect the network.)

We have:

$$\mathcal{N} = \{1, \dots, n\} = [n] \text{ and} \\ \mathcal{L} = \{\mathcal{L}_1, \dots, \mathcal{L}_n\} \text{ with } \mathcal{L}_i = (i, i + 1) \text{ for } 1 \leq i < n \text{ and } \mathcal{L}_n = (n, 1).$$

Since $m = n$, \mathbf{K} is an $n \times n$ matrix:

$$\mathbf{K} = \begin{pmatrix} 1 & & & & -1 \\ -1 & 1 & & & \\ & -1 & 1 & & \\ & & \ddots & \ddots & \\ & & & 1 & \\ & & & & -1 & 1 \end{pmatrix}.$$

(All unspecified elements are 0).

Note that the *columns* of \mathbf{K} correspond to the lines of the network.

□

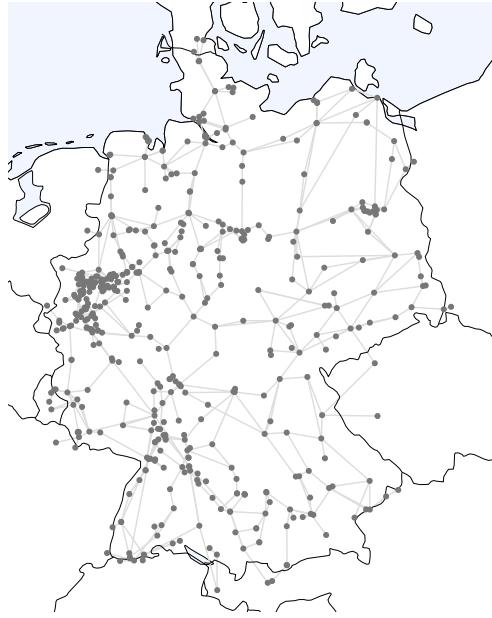


Figure 5.3: The $n = 489$ buses and $m = 695$ lines of the SciGRID network. A description of this dataset is given in Part II.

Example 5.2.4 (SciGRID Germany). In Part II, we will apply our theory to the SciGRID dataset, which contains the network shown in Figure 5.3. This network is much more realistic than the previous examples, as it is based on the real-world structure of the transmission network in Germany.

It is common for transmission networks to have a well-connected ‘core’, with some branches out of the core towards the outer regions of the network. This means that in general, $m > n$.

Indeed, in this network we have $n = 489$ and $m = 695$. The vertex-edge incidence matrix \mathbf{K} has dimensions 489×695 , and is *sparse*: most entries are zero.

It is important to note that this is only a *section* of the actual transmission network of continental Europe, which is highly connected among different countries. As we will discuss in Section 6.1, accurate datasets of continental Europe do exist, but they are hard to obtain and analyse. \natural

5.3 Power grid state

The *state* of the network describes how the transmission network is being used (the (real and reactive) power injected at each node, and the voltage magnitudes) and how the electric circuit responds (voltage angles and (complex) line currents). More precisely, we use three physical quantities used in AC circuit analysis to describe the grid state:

Definition 5.3.1. A *grid state* of an (n, m) -grid structure is defined as a tuple $(\mathbf{S}, \mathbf{V}, \mathbf{I})$, where

- $\mathbf{S} \in \mathbb{C}^n$ is the *complex power injection vector*;
- $\mathbf{V} \in \mathbb{C}^n$ is the *bus voltage vector*;
- $\mathbf{I} \in \mathbb{C}^m$ is the *line current vector*. (Currents are directed along digraph edges.)

Uitleg van AC circuits, real and reactive power, complexe grootheden, etc mist nog.
In Hoofdstuk 3 van von Meier (2006) is het erg duidelijk uitgelegd.

U instead
of V? Not
common in
lit

5.4 State validity

Given an (n, m) -grid structure $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$, only some states are physically possible. A state that satisfies Kirchoff's Laws and Ohm's Law will be called *valid*. Of course, since we are studying a real-world system, we are mainly interested in states that are valid, or at least close to being valid (in the sense of *DC-valid*, see Section 5.6).

5.4.1 Circuit representation

An (n, m) -grid structure $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$ represents an electrical circuit, consisting of impedances and AC sources. A *valid* grid state $(\mathbf{S}, \mathbf{V}, \mathbf{I})$ corresponds to a physical state of the circuit. From the mathematical structure, we will construct the corresponding electric circuit in two layers, as follows:

In the first layer, each node i in \mathcal{N} becomes a node in the circuit. The value of V_i is the electric potential of that node, relative to ground.

A line $\mathcal{L}_k = (i, j)$ is modelled as an impedance element⁴ (—□—) with admittance η_k between the two nodes i and j . The value of I_k is the current flowing through the impedance from i to j .

check sign

See Figure 5.4 for the first constructed layer. This is not the final circuit: we have not yet added generators and loads to the circuit! Also, the transmission lines have no return wire. This means that there is no closed loop between two nodes, and therefore no energy can be transmitted.

To construct the second layer, we add a new component to each node $i \in \mathcal{N}$, which can be seen as the collection of AC sources (generators) and impedances (loads), connected in parallel between the node and ground. The exact way that loads and generators are connected to the node is not important,⁵ so we will simply state that this component:

- sustains a potential difference (which is V_i);⁶

⁴complex-valued resistor

⁵This would be a circuit comprising the medium and low-voltage networks connected to the node, including every generator, fridge and phone charger that it serves. This is a common (and necessary) abstraction in power grid analysis.

⁶In physical systems, the *operating voltage* $|V_i|$ (remember that V is complex) can be controlled by power plant operators by adjusting excitation current of a generator. The *phase angle* $\theta_j = \text{Arg}(V_j)$ can be controlled by adjusting the amount of energy (steam) supplied to a generator.

Both methods are an indirect form of control, which also affects all other nodes in the network. In fact, *maintaining* a constant operating voltage and phase angle is a complicated task, requiring continuous adjustments to generator operation. Section 4.3 of von Meier (2006) covers this topic in more detail.

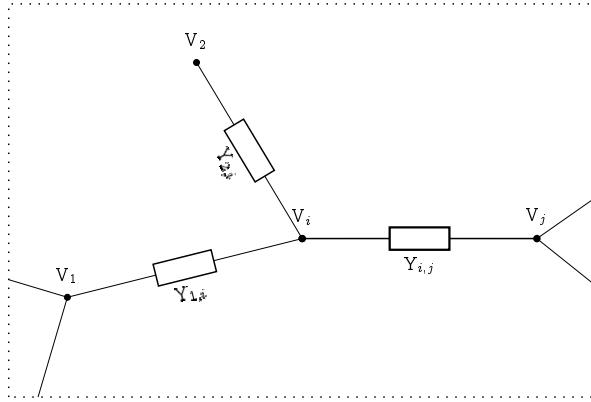


Figure 5.4: A section of a transmission network, showing the line (i, j) . Two more nodes, both connected to i , are also shown. Note that this is only one layer of the electric circuit used in the model. In the full model (Figure 5.5), each transmission line forms a closed circuit, allowing current to flow.

- either supplies or draws a current, such that the amount of power generated or consumed by the component equals S_i (when S_i is positive or negative, respectively).

We will call this aggregation of generators and loads a *power injector* (——).

Each power injector is connected to a node on one end, and to a ground terminal on the other. In electric circuit theory, a ground terminal represents a direct connection to a universal ground: the ‘zero’ reference of electric potential. One could say that between two different ground terminals, there exists a zero-impedance link connecting the two. We now have a simple closed circuit between any two nodes connected by a transmission line, consisting of a power injector for the first node, an impedance between the two nodes, a power injector for the second node and a ground link back to the first node.

The complete, two-layer model is shown in Figure 5.5.

Justify conductive ground wire in a 3-phase system

5.4.2 Kirchoff’s Voltage Law (KVL) & Ohm’s Law

For each line $\mathcal{L}_k = (i, j)$, we can apply Kirchoff’s Voltage Law to the loop “ground $\rightarrow i \rightarrow j \rightarrow$ ground”, as shown in Figure 5.5. This gives us:

$$V_i + \Delta V_k + -V_j = 0,$$

where ΔV_k is the electric potential of the line impedance. This potential relates to the line current according to Ohm’s Law:

$$I_k = \Delta V_k \cdot \eta_k = (V_j - V_i) \cdot \eta_k.$$

Since the k th column of \mathbf{K} (which corresponds to the line $\mathcal{L}_k = (i, j)$) has two non-zero entries: $K_{i,k} = 1$ and $K_{j,k} = -1$, we can write:

$$I_k = (V_j - V_i) \cdot \eta_k = -(K^* V)_k \eta_k.$$

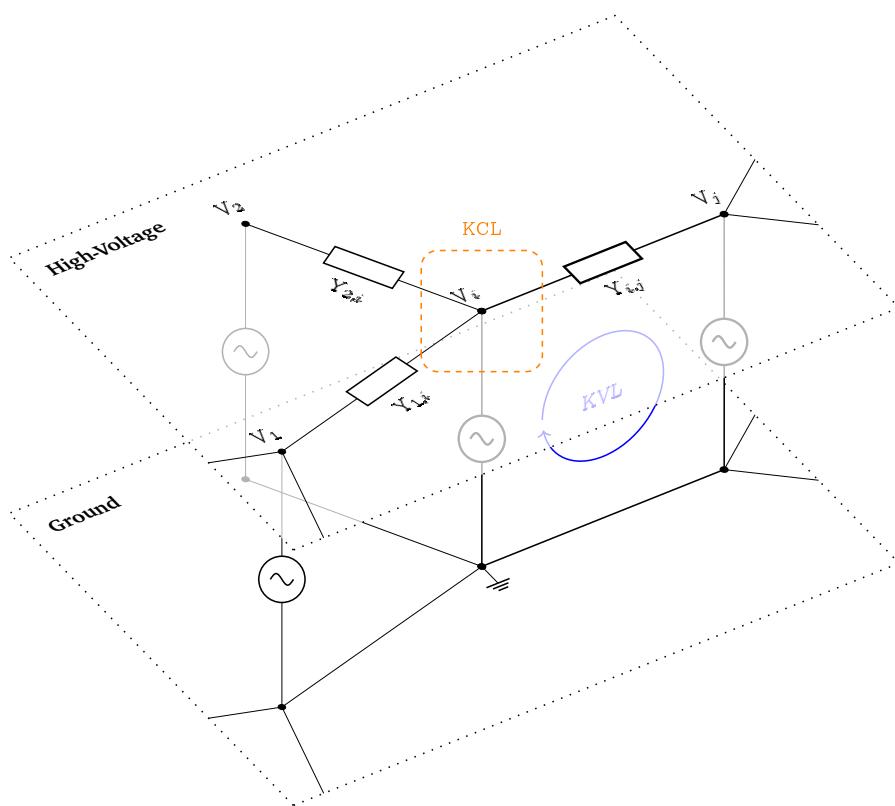


Figure 5.5: The electric model of the transmission network, showing the line (i, j) and two other nodes. A node is represented by a single component ($\textcircled{?}$), which is the aggregation of all generators and loads connected to that node. A transmission line is modelled as an impedance (\square), a complex-valued resistor. The ground 'wires' have zero resistance.

KVL is applied to each line, by traversing the loop drawn in blue.

KCL is applied to each node, by summing all currents entering and leaving the orange area.

This holds for every $k \in [m]$, and this system of equations can be written compactly as:

$$\mathbf{I} = i \operatorname{diag}(i\boldsymbol{\eta}) \mathbf{K}^* \mathbf{V}$$

Written in this form, we see that when $i\boldsymbol{\eta}$, \mathbf{C} and \mathbf{V} are purely real, then \mathbf{I} is purely imaginary. Physically, this means that line current is always 90° out of phase with node voltage. (Or it means that current is out of phase with voltage differences? Which are voltage angle differences?)

Writing node voltages in a circuit already implies that KVL holds.

5.4.3 Kirchoff's Current Law (KCL)

Using KVL and Ohm's Law, we found a relation between line current and node voltages. We can use KCL to TODO

Let's apply KCL to every high-voltage node in the electric circuit, as shown in Figure 5.5. This gives us:

$$\mathbf{S} + \overline{(\mathbf{K}\mathbf{I})} * \mathbf{V} = \mathbf{0}$$

which is the sum of line currents entering the node, minus the sum of line currents leaving the node.

Show derivation of (S-KCL) from KCL in the last illustration

5.4.4 Validity conditions

intro

Definition 5.4.1. Given an (n, m) -grid structure $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$, a grid state $(\mathbf{S}, \mathbf{V}, \mathbf{I})$ is *valid* if it satisfies the *KVL-Ohm equality*:

$$\mathbf{I} = i \operatorname{diag}(i\boldsymbol{\eta}) \mathbf{K}^* \mathbf{V} \quad (\text{KVL-Ohm})$$

and the *KCL equality*:

$$\mathbf{S} + \overline{(\mathbf{K}\mathbf{I})} * \mathbf{V} = \mathbf{0}. \quad (\text{S-KCL})$$

Remark. In physical terms, the *KVL-Ohm equality* states:

Each line $\mathcal{L}_k = (i, j)$ satisfies Ohm's Law ($I = VY$), where:
 $I = I_k, \quad V = V_i - V_j, \quad Y = \eta_k$

and the *KCL equality* states:

At each node i , the sum of power injected at the node, S_i ,
and power injected from the grid, must equal 0.

Proposition 5.4.2. Given a grid structure and state as in Definition 5.4.1, the following are equivalent:

- i. The grid state is valid.
- ii. The grid state satisfies (KVL-Ohm) and (S-KCL).
- iii. The grid state satisfies (KVL-Ohm), and each node i satisfies the node flow equation:

$$S_i = i \sum_{j=1}^n \bar{L}_{i,j} |V_i| |V_j| e^{i(\theta_i - \theta_j)} \quad \text{for each } i \in [n], \quad (5.1)$$

$$\text{where } \mathbf{L} = \mathbf{K} \operatorname{diag}(i\eta) \mathbf{K}^* \quad (5.2)$$

and $\boldsymbol{\theta} \in \mathbb{R}^n$ is the vector of voltage angles, i.e. $\theta_j = \operatorname{Arg}(V_j)$ (the principle argument of V_j). We call \mathbf{L} the nodal susceptance matrix (?).

Remark. Note that (5.1) does not depend on \mathbf{I} . This means that a valid state is uniquely determined by \mathbf{S} and \mathbf{V} , since \mathbf{I} can be computed from \mathbf{V} using (KVL-Ohm).

Remark. Writing in real and imaginary components, we get the node flow equations for real and reactive power for each node $i \in [n]$:

$$P = \Re(S_i) = \sum_{j=1}^n |V_i| |V_j| [\Re(M_{i,j}) \cos(\theta_i - \theta_j) + \Im(M_{i,j}) \sin(\theta_i - \theta_j)] \quad (5.3)$$

$$Q = \Im(S_i) = \sum_{j=1}^n |V_i| |V_j| [\Re(M_{i,j}) \sin(\theta_i - \theta_j) - \Im(M_{i,j}) \cos(\theta_i - \theta_j)] \quad (5.4)$$

In literature on the subject, the node flow equation is often given in this form.

We will later study so called *DC-valid* grid structures, where the values of \mathbf{M} are purely imaginary. If so, (5.3) simplifies to:

$$P = \Re(S_i) = \sum_{j=1}^n \Im(M_{i,j}) |V_i| |V_j| \sin(\theta_i - \theta_j),$$

which tells us that in a network of just two nodes and one line with purely imaginary admittance, the amount of real power transmitted is proportional to $\sin(\theta_2 - \theta_1)$.⁷

Proof. (i) \iff (ii) is true by definition.

Suppose the grid state satisfies (KVL-Ohm). We have

$$\begin{aligned} \mathbf{S} + \overline{(\mathbf{K}\mathbf{I})} * \mathbf{V} &= \\ \mathbf{S} + \overline{(i\mathbf{K} \operatorname{diag}(i\eta) \mathbf{K}^* \mathbf{V})} * \mathbf{V} &= \\ \mathbf{S} + \overline{(i\mathbf{L}\mathbf{V})} * \mathbf{V} &= \mathbf{0} \end{aligned}$$

iff for each $i \in [n]$

⁷The quantity $\theta_2 - \theta_1$ is called the *power angle* of the transmission line, a common measure of the amount of power being transmitted. As discussed in Section ??, a power angle greater than 45° will cause the nodes to lose synchronicity, making power transmission between the two nodes impossible. For long lines (over 100km), this *stability limit* places an upper limit on the amount of power that a line can transmit. For shorter lines, the *thermal limit* dominates.

\mathbf{M} should be
 $\pm i\mathbf{L}$

is this New-
ton's heat
equation
with \mathbf{M} the
discrete
Laplacian?

$$\begin{aligned}
S_i &= - \overline{\left(\sum_{j=1}^n i L_{i,j} V_j \right)} V_i \\
&= - \left(\sum_{j=1}^n -i \bar{L}_{i,j} \bar{V}_j \right) V_i \\
&= i \sum_{j=1}^n \bar{L}_{i,j} V_i \bar{V}_j \\
&= i \sum_{j=1}^n \bar{L}_{i,j} |V_i| e^{i\theta_i} |V_j| e^{-i\theta_j} \\
&= i \sum_{j=1}^n \bar{L}_{i,j} |V_i| |V_j| e^{i(\theta_i - \theta_j)},
\end{aligned}$$

proving (ii) \iff (iii). 

5.5 Power Flow

In the previous section, we derived a fundamental result: the *node flow equation* (5.1). Recall from Section ?? that the *power flow problem* entails the following:

*Given an (n, m) -grid structure $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$, and a power injection \mathbf{S} ,
find \mathbf{V} and \mathbf{I} such that $(\mathbf{S}, \mathbf{V}, \mathbf{I})$ is a valid state.*

Or put more simply:

*Given the production or consumption at each node,
find the current flowing through each line.*

It turns out that the easiest way to solve this problem is to solve the node flow equation to obtain \mathbf{V} . Once \mathbf{V} is known, one can easily compute \mathbf{I} using KVL-Ohm, giving a state $(\mathbf{S}, \mathbf{V}, \mathbf{I})$ that is valid by construction.

The node flow equation is a system of non-linear equations, and no closed-form solution is known to exist in general. Fortunately, solving the node flow equation is essentially a root-finding problem. This means that well-established techniques, such as the Newton-Raphson algorithm, can be used to find a numerical solution.

Difficulty of finding initial values that converge: flat start. Is DC approx used as initial value?

5.6 DC approximation

“DC approximation” is a name given to a collection of assumptions/approximations, described below. The name ‘DC’ refers to the approximation that the network is decoupled. Unlike the abbreviation might suggest, the power grid is still modelled as an AC network.

Scott1974
for the ori-
gin of the
DC approxi-
mation

intro

Compare the following with Definitions 5.2.1 and 5.3.1.

Definition 5.6.1. Suppose $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$ is an (n, m) -grid structure, with a grid state $(\mathbf{S}, \mathbf{V}, \mathbf{I})$.

- If $\boldsymbol{\eta} \in i\mathbb{R}^m \subseteq \mathbb{C}^m$ (i.e. $\boldsymbol{\eta}$ has purely imaginary values) then the grid structure *satisfies the DC approximation*.⁸
- If $\mathbf{S} \in \mathbb{R}^n \subseteq \mathbb{C}^n$ then the grid state *satisfies the DC approximation*. (Note that \mathbf{V} and \mathbf{I} need not be real-valued.)
- If $\mathbf{V} \in \mathbb{T}^n \cdot V_{op} \subseteq \mathbb{C}^n$ (i.e. $|V_i| = V_{op}$ for each node i) for some *operating voltage* $V_{op} \in \mathbb{R}_{\geq 0}$, then the grid state admits a *flat profile*.

In the special case $V_{op} = 1$, the grid state admits a *normalised profile*.

physics:
conductance
is neglected

By replacing the \exp function in (5.1) by $z \mapsto 1+z$ (the first two terms of the Maclaurin series of \exp) we get the *approximate node flow equation*. These two conditions are different, but as we will later see, similar for networks with small phase shifts. Compare the following with Definition 5.4.1 and (5.1).

Definition 5.6.2. Given an (n, m) -grid structure $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$, a grid state $(\mathbf{S}, \mathbf{V}, \mathbf{I})$ is *DC-valid* if it satisfies the *KVL-Ohm equality*:

$$\mathbf{I} = i \operatorname{diag}(i\boldsymbol{\eta}) \mathbf{K}^* \mathbf{V} \quad (\text{KVL-Ohm})$$

and each node i satisfies the *approximate node flow equation*:

$$S_i = i \sum_{j=1}^n \bar{L}_{i,j} |V_i| |V_j| (1 + i(\theta_i - \theta_j)) \quad \text{for each } i \in [n]. \quad (5.5)$$

physics:
only phase
shifts are
considered,
unit is p.u.
instead of
Volts

hyp: a (DC-?) valid state can only exist if the structure and state both satisfy the DC approx (otherwise no line drop can occur?)

discuss line drop

this is also approximated: CV is linearised.

Theorem 5.6.3. Suppose that a grid structure and state satisfy the DC approximation and that the state admits a flat, normalised profile. Then the approximated node flow equation is linear and real:

$$\mathbf{S} = \mathbf{L}\boldsymbol{\theta}. \quad (5.6)$$

Proof. For each node i , we have:

$$\begin{aligned} S_i &= i \sum_{j=1}^n \bar{L}_{i,j} |V_i| |V_j| (1 + i(\theta_i - \theta_j)) \\ &= i \sum_{j=1}^n L_{i,j} |V_i| |V_j| - \sum_{j=1}^n L_{i,j} |V_i| |V_j| (\theta_i - \theta_j) \end{aligned}$$

⁸In Nesti et al., we have $\beta = i\boldsymbol{\eta}$. Transmission line impedance ($Z = R + iX$) is dominated by inductance, which is positive reactance (X). Resistance (R) is always positive for passive components. Therefore, Z lies in the top-right quadrant of \mathbb{C} . Then the admittance, $Y = 1/Z = G + iB$, lies in the bottom-right quadrant of \mathbb{C} . In the DC approximation, line conductance (G) is neglected, so ($Y = iB$ with $B < 0$). Therefore, $\beta_k = i\eta_k = iY = -B > 0$ is the *susceptance of line k, with reversed sign*.

If we assume a DC state ($S_i \in \mathbb{R}$):

$$\begin{aligned}
&= - \sum_{j=1}^n L_{i,j} |V_i| |V_j| (\theta_i - \theta_j) \\
&= - \sum_{j=1}^n L_{i,j} |V_i| |V_j| \theta_i + \sum_{j=1}^n L_{i,j} |V_i| |V_j| \theta_j \\
&= -\theta_i |V_i| \sum_{j=1}^n L_{i,j} |V_j| + |V_i| \sum_{j=1}^n L_{i,j} |V_j| \theta_j
\end{aligned}$$

If we assume a flat profile ($|V_i| = |V_j| = V_{op}$ for every $i, j \in [n]$):

$$= -\theta_i V_{op}^2 \sum_{j=1}^n L_{i,j} + V_{op}^2 \sum_{j=1}^n L_{i,j} \theta_j$$

The rows of L add up to 0:

$$\begin{aligned}
&= V_{op}^2 \sum_{j=1}^n L_{i,j} \theta_j \\
&= V_{op}^2 (\mathbf{L}\boldsymbol{\theta})_i
\end{aligned}$$

If we assume V to be normalised (if V is measured in p.u., instead of Volts):

$$= (\mathbf{L}\boldsymbol{\theta})_i$$

and we find:

$$\mathbf{S} = \mathbf{L}\boldsymbol{\theta}$$



Appendix: give a direct formula for \mathbf{L}

compute \mathbf{L} for the example networks

give an alternative interpretation of \mathbf{L} or \mathbf{L} : discrete laplacian

discuss the kernel of \mathbf{L} : it should follow from graph theoretical arguments that the kernel is spanned by $(1, 1, \dots, 1)^*$, such that the nullity of \mathbf{L} is 1. This corresponds to the fact that phase angle is a relative quantity. (The state remains (DC-)valid when increasing the phase angle at each node by the same amount. (If $\mathbf{S} = \mathbf{L}\boldsymbol{\theta}$ and $\boldsymbol{\theta}_0 \in \ker \mathbf{L}$, then $\mathbf{S} = \mathbf{L}(\boldsymbol{\theta} + \boldsymbol{\theta}_0)$.))

There are two paths to take after this point:

1: Fix the phase angle of the slack bus (to 0), which corresponds to taking the $n - 1 \times n - 1$ submatrix of \mathbf{L} , I think. **This is the approach of PyPSA, which might explain small differences in line flow.**

2: Leave \mathbf{L} as-is, and consider the *Moore-Penrose pseudo-inverse* of \mathbf{L} . This is the approach of Nesti et al., which they attribute to 'distributive slack': not fixing a single slack bus.

5.6.1 Usefulness

Real transmission networks do not satisfy the DC approximation and, in general, a DC-valid state is not (physically) valid. Yet, using these two approximations has one important property: the approximated node flow equation becomes *linear*. This has a number of advantages:

- Solving the Power Flow problem (i.e. computing line flows induced by a power injection vector) becomes trivial. As we will see in Section 5.7,

ref

ugh

- A linear power flow is crucial for the study of stochastic power injections, since it can be used to transform a probability distribution (like a multivariate normal distribution) without losing its structure.

be specific

5.6.2 Accuracy

The DC approximation is a useful tool for understanding the complex nature of transmission networks. Therefore, it is crucial to verify that the DC approximation is, in fact, a good approximation, when real-world networks are studied. More precisely, one should ask:

1. How close is a DC-valid state to being valid? More precisely, when the approximate node flow equation (5.5) holds, what is the mismatch between the left hand and right hand side of the node flow equation (5.1)?
2. How close are real-world grid structures to satisfying the DC approximation?

The first question is answered in Proposition 5.6.5, where an upper bound is derived for the power mismatch. It shows that the mismatch is bounded by the *squares* of local differences in phase angles (i.e. $\theta_i - \theta_j$ for line (i, j)). Purchala et al. (2005) have shown that in the Belgian transmission network, all phase differences are below 7° , and 94% of lines have a phase difference below 2° .

europe

The second question

SciGRID

acc of DC approx struc vs acc of DC valid state

Purchala

Lemma 5.6.4. There exists $K \in \mathbb{R}_{>0}$ such that

$$|\exp ix - (1 + ix)| = K|x|^2 \quad \text{for every } -2\pi \leq x \leq 2\pi.$$

literature:
Purchala
et al. (2005);
Overbye
et al. (2004)

Proof. **A proof using complex analysis.**⁹ The complex (entire) function $z \mapsto \exp z$ is defined by the power series

$$z \mapsto \sum_{k=0}^{\infty} \frac{z^k}{k!} = 1 + z + z^2 \left(\frac{z^0}{2!} + \frac{z^1}{3!} + \dots \right)$$

Move to appendix?

Find an upper bound for K ,
 $K = 0.5$ works

which has infinite radius of convergence, and is continuous on \mathbb{C} .

The functions $z \mapsto \frac{1}{z^2}$, $z \mapsto \exp z$ and $z \mapsto 1 + z$ are all holomorphic on $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$, and so the function

$$g : \mathbb{C}^* \rightarrow \mathbb{C} \quad g : z \mapsto \frac{1}{z^2}(\exp z - (1 + z)) \quad (5.7)$$

0^0

is holomorphic on \mathbb{C}^* , with a removable singularity at 0. The (unique) extension of g to \mathbb{C} is an entire function, and by construction:

$$\exp z = 1 + z + z^2 g(z) \quad \text{for each } z \in \mathbb{C}.$$

Since g is entire, it is continuous on \mathbb{C} . $I = [-i2\pi, i2\pi]$ is a compact subset of \mathbb{C} , so g is bounded on I , proving the result. \checkmark

Proposition 5.6.5. Suppose $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$ is an (n, m) -grid structure, with a state $(\mathbf{S}, \mathbf{V}, \mathbf{I})$ that admits a flat profile with operating voltage V_{op} .

If the state is DC-valid, then there exists $K \in \mathbb{R}_{\geq 0}$ such that for each node i :

$$\begin{aligned} \left| \mathbf{S}_i - i \sum_{j=1}^n \bar{\mathbf{L}}_{i,j} |\mathbf{V}_i| |\mathbf{V}_j| e^{i(\theta_i - \theta_j)} \right| &\leq KV_{op}^2 \sum_{j=1}^n |\mathbf{L}_{i,j}| (\theta_i - \theta_j)^2 \\ &\leq KV_{op}^2 \|\boldsymbol{\eta}\|_\infty \|\mathbf{K}^* \boldsymbol{\theta}\|_2^2. \end{aligned}$$

Remark. This result states that if the grid state is DC-valid, and the power angles (i.e. $\theta_i - \theta_j$ for line (i, j)) are low, then the state is close to also being valid.

Quantitatively, it tells us that for a given node i , the 'error' resulting from using the approximate node flow equation (5.5) is proportional to the squares of phase angles of lines that connect to i .

A more important result would be an upper limit for the error in line flow, instead of the error in node flow

Proof. Suppose $i \in [n]$.

Choose a $K \in \mathbb{R}_{\geq 0}$ for which Lemma 5.6.4 holds. The state is DC-valid, so we can

⁹For an introduction, see Garling (2014).

this follows from the proof, not the statement itself

substitute (5.5) for S_i :

$$\begin{aligned}
& \left| S_i - \sum_{j=1}^n \bar{M}_{i,j} |V_i| |V_j| e^{i(\theta_i - \theta_j)} \right| \\
&= \left| i \sum_{j=1}^n \bar{L}_{i,j} |V_i| |V_j| (1 + i(\theta_i - \theta_j)) - i \sum_{j=1}^n \bar{L}_{i,j} |V_i| |V_j| e^{i(\theta_i - \theta_j)} \right| \\
&= V_{op}^2 \left| \sum_{j=1}^n \bar{L}_{i,j} (e^{i(\theta_i - \theta_j)} - (1 + i(\theta_i - \theta_j))) \right| \\
&\leq V_{op}^2 \sum_{j=1}^n |\bar{L}_{i,j}| \left| e^{i(\theta_i - \theta_j)} - (1 + i(\theta_i - \theta_j)) \right| \quad (\text{triangle inequality}) \\
&\leq KV_{op}^2 \sum_{j=1}^n |\bar{L}_{i,j}| (\theta_i - \theta_j)^2 \quad (\text{Lemma 5.6.4}) \\
&= KV_{op}^2 \left[\sum_{j=i}^n |\bar{L}_{i,j}| (\theta_i - \theta_j)^2 + \sum_{\substack{j \neq i \\ i,j \text{ connected}}} |\bar{L}_{i,j}| (\theta_i - \theta_j)^2 + \sum_{\substack{j \neq i \\ i,j \text{ not connected}}} |\bar{L}_{i,j}| (\theta_i - \theta_j)^2 \right] \\
&= KV_{op}^2 \left[|\bar{L}_{i,i}| (\theta_i - \theta_i)^2 + \sum_{\substack{j \neq i \\ i,j \text{ connected}}} |\bar{L}_{i,j}| (\theta_i - \theta_j)^2 + \sum_{\substack{j \neq i \\ i,j \text{ not connected}}} 0 \cdot (\theta_i - \theta_j)^2 \right] \\
&= KV_{op}^2 \sum_{\substack{j \neq i \\ i,j \text{ connected}}} |\bar{L}_{i,j}| (\theta_i - \theta_j)^2 \\
&\leq KV_{op}^2 \sum_{\substack{\mathcal{L}_k = (a,b) \in \mathcal{L}}} |\bar{L}_{a,b}| (\theta_a - \theta_b)^2 \\
&= KV_{op}^2 \sum_{\substack{\mathcal{L}_k = (a,b) \in \mathcal{L}}} |\eta_k| (K^* \theta)_k^2 \\
&= KV_{op}^2 \|\boldsymbol{\eta} * K^* \boldsymbol{\theta} * K^* \boldsymbol{\theta}\|_1 \quad (\text{in } \ell^1) \\
&\leq KV_{op}^2 \|\boldsymbol{\eta}\|_\infty \|K^* \boldsymbol{\theta} * K^* \boldsymbol{\theta}\|_1 \quad (\text{Hölder's inequality}) \\
&= KV_{op}^2 \|\boldsymbol{\eta}\|_\infty \|K^* \boldsymbol{\theta}\|_2^2
\end{aligned}$$



Discuss the PDEs used for computing the PF?

5.7 Linear Power Flow

Physically, power does not actually flow. (Although *energy* does). A better term would be: *flow power*, since a high power flow from A to B is actually a *powerful flow of energy* from A to B.

In the context of line overloads, we are only interested in line *current*, which can be seen as proportional to the amount of power being transmitted by the line. (Again, power is not a physical quantity that can be transmitted.) In a flat, normalised profile, power flow and line current are identical. To follow general convention, we will talk about power flow instead of line current. For example, line ratings are often given in Watts, not Amperes. (Even though the amount energy dissipated by a line, I^2R , depends only on line current. At a nearly constant operating voltage, however, these quantities are proportional to each other.)

DC approx, flat, normalised state and DC valid:

pseudoinverse:

$$\mathbf{p} = \mathbf{L}\boldsymbol{\theta}$$

so there exists L^+ such that

$$\boldsymbol{\theta} = L^+ \mathbf{p}$$

this is the moore-penrose pseudo-inverse,

My DC approximated KVL-Ohm is incorrect, it should be: $\mathbf{I} = i \operatorname{diag}(i\eta) \mathbf{C} \boldsymbol{\theta} V_{op}$.

$$\hat{\mathbf{f}} = -iV_{op}\mathbf{I} = -iV_{op}^2 i \operatorname{diag}(i\eta) \mathbf{K}^* \boldsymbol{\theta} = \operatorname{diag}(i\eta) \mathbf{K}^* \mathbf{L}^+ \mathbf{p}.$$

(We assumed a normalised profile, so $V_{op} = 1$.)

If the line thresholds are $\mathbf{W} = (W_1, \dots, W_m)^* \in \mathbb{R}^m$, then we can define the *normalised line flow* as:

$$\mathbf{f} = \operatorname{diag}(\mathbf{W})^{-1} \hat{\mathbf{f}}$$

and we find:

$$\mathbf{f} = \mathbf{F} \mathbf{p} \quad (\text{LPF})$$

$$\text{where } \mathbf{F} = \operatorname{diag}(\mathbf{W})^{-1} \operatorname{diag}(i\eta) \mathbf{K}^* \mathbf{L}^+$$

Dit is

This is a linear transformation from a power injection vector \mathbf{p} to the normalised line flow \mathbf{f} that induces it.

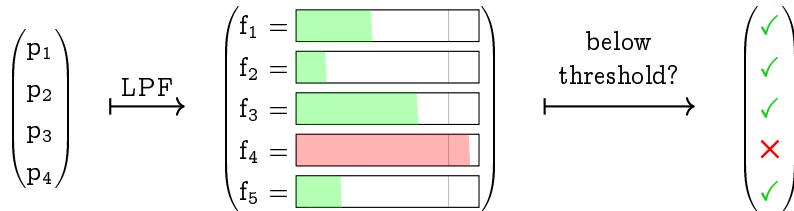
\mathbf{F} is not the unique transformation with this property (otherwise \mathbf{F} would be square and non-singular). Does \mathbf{F} minimise $\|\mathbf{f}\|$? \mathbf{F}

Leg het verband tussen de LPF en het hoofdstuk over grafen: de af

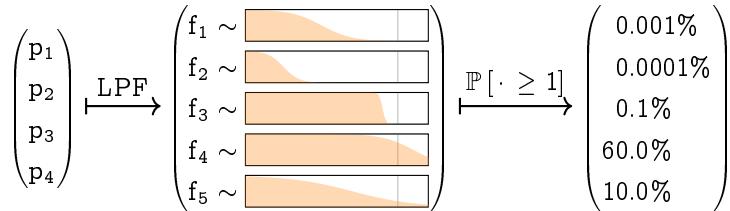
line drop:
(real) power
flowing out
of a node
is slightly
more than
power

5.8 Stochastic power injections

Using the linear transformation \mathbf{F} that we just derived, we can compute the normalised line flow that a *zero-sum* power injection \mathbf{p} induces. This is a useful result: for example, one could check whether a generator configuration is *admissible* by writing down the injection \mathbf{p} associated to this configuration, and checking that no value of $\mathbf{F}\mathbf{p}$ is greater than 1. (Since we *normalised* the line flows, each line has unit 'threshold'.)



Things get even more interesting when \mathbf{p} is a *stochastic variable*. In this case, \mathbf{f} is also a stochastic variable! In fact, given a probability distribution function for \mathbf{p} , we can use \mathbf{F} to compute the *probability distribution function* of \mathbf{f} . Using this probability distribution, we can now answer questions such as: "What is the probability that line i overloads?" ($\mathbb{P}[|f_i| \geq 1]$) Or: "What is the probability that line i overloads, given that line j is operating at 95% capacity?" ($\mathbb{P}[|f_i| \geq 1 \mid f_j = 0.95]$).



5.8.1 Normally distributed power injection

Following Nesti et al. (2018a), we model \mathbf{p} to be *multivariate normally distributed*:

$$\mathbf{p} \sim \mathcal{N}(\boldsymbol{\mu}_p, \Sigma_p)$$

where $\boldsymbol{\mu}_p$ is the mean power injection, which is the sum of deterministic generation and expected stochastic generation, minus the load. Σ_p is the *power injection correlation matrix*, which can be estimated from historical generation series. When power injection at different nodes is correlated (because of correlated weather), this matrix is non-diagonal.

Because \mathbf{F} is a linear transformation, the vector of line flows \mathbf{f} is (multivariate) Gaussian distributed (Theorem 1.4.6), and its distribution is given by

$$\mathbf{f} \sim \mathcal{N}(\boldsymbol{\mu}_f, \Sigma_f), \quad \text{where} \quad \boldsymbol{\mu}_f = \mathbf{F}\boldsymbol{\mu}_p \quad \text{and} \quad \Sigma_f = \mathbf{F}\Sigma_p\mathbf{F}^*. \quad (5.8)$$

For realistic networks we have $m > n$, which means that \mathbf{F} is not surjective. Then Σ_f is not injective, meaning that \mathbf{f} is Gaussian, but not normally distributed (Theorem 1.4.5).

grafiekjes
zijn van $|f|$,
niet f .

grafiekjes
zijn van $|f|$,
niet f .

5.8.2 Overload probabilities

For a line l , the probability distribution of the current through that line is simply the marginal distribution f_l . Therefore, the probability of an emergent failure of line l is given by:¹⁰

$$\mathbb{P}[|f_l| \geq 1] = \mathbb{P}[f_l \leq 1] + \mathbb{P}[f_l \geq 1]$$

From Theorem 1.4.7 it follows that $f_l \sim \mathcal{N}(\mu_{fl}, \Sigma_{fl})$, and $\mathbb{P}[|f_l| \geq 1]$ can now be computed using standard techniques.

The probability of *any* emergent failure is $\mathbb{P}[\exists_{l \in [m]} |f_l| \geq 1]$, which can be approximated by an upper and lower bound:

$$\max_{l \in [m]} \mathbb{P}[|f_l| \geq 1] \leq \mathbb{P}[\exists_{l \in [m]} |f_l| \geq 1] \leq \sum_{l \in [m]} \mathbb{P}[|f_l| \geq 1].$$

Trivially, the most likely line flow, given that any emergent failure occurred, coincides with most likely line flow, given that the most vulnerable line failed.

Or estimated using the LDP

5.8.3 Most likely power injection

Now that we have identified the most vulnerable lines in the network, we naturally want to simulate the effect that the failure of one of these lines will have. When we remove the line from our model, we get a new LPF matrix, which can be used to check the currents through all other lines, after the initial failure. But what power injection should be used? Because we are studying the *hypothetical* failure of a line, we do not yet know the exact power injection that caused it.

The classical approach is to use the nominal power injection, μ_p . This is exactly what we would do when studying regular line failures (caused by a fallen tree, for example). In our case, however, we assumed that the line failed because of an *overload*, which tells us that the power injection must have deviated from its nominal value.

Because we have estimated a probability distribution for p , we can find the *most likely power injection, given that line l overloaded*. We can compute this injection explicitly, leveraging the fact that the LPF map is linear.

Theorem 5.8.1. Suppose a grid with LPF F has a $\mathcal{N}(\mu_p, \Sigma_p)$ -distributed power injection p . The most likely power injection $\tilde{p}^{(l)}$, given the emergent failure of a line l , is uniquely given by

$$\tilde{p}^{(l)} = \mu_p + \frac{\text{sign}(\mu_{fl}) - \mu_{fl}}{\Sigma_{fl}} \Sigma_p F^* e_l \quad (5.9)$$

when $\mu_{fl} \neq 0$. Otherwise, there are two injections that maximise the conditional probability of p , which are given by

$$\tilde{p}^{(l,+)} = \mu_p + \frac{1}{\Sigma_{fl}} \Sigma_p F^* e_l \quad \text{and} \quad \tilde{p}^{(l,-)} = \mu_p + \frac{-1}{\Sigma_{fl}} \Sigma_p F^* e_l.$$

¹⁰Remember that the sign of f_l corresponds to the direction of current through the line. The line orientations were chosen arbitrarily, and only have meaning in our bookkeeping.

Proof. The set of power injections associated with the failure event of line l is a union of two parallel planes in \mathbb{R}^n . Indeed, the condition $f_l = 1$ can be written as:

$$f_l = 1 \iff (\mathbf{F}\mathbf{p})_l = 1 \iff \mathbf{e}_l^* \mathbf{F}\mathbf{p} = 1 \iff \langle \mathbf{F}^* \mathbf{e}_l, \mathbf{p} \rangle = 1$$

which is the equation defining the plane with pillar $\mathbf{F}^* \mathbf{e}_l$. Similarly, the condition $f_l = -1$ is satisfied if and only if \mathbf{p} is contained in the plane with pillar $-\mathbf{F}^* \mathbf{e}_l$.

We can now apply Theorem 1.4.12 to each pillar to find the mode of \mathbf{p} , given $f_l = 1$, or $f_l = -1$, respectively:

$$\begin{aligned} \tilde{\mathbf{p}}^{(l,+)} &= \mu_{\mathbf{p}} + \frac{1 - \langle \mu_{\mathbf{p}}, \mathbf{F}^* \mathbf{e}_l \rangle}{\langle \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l, \mathbf{F}^* \mathbf{e}_l \rangle} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l \\ &= \mu_{\mathbf{p}} + \frac{1 - \langle \mathbf{F} \mu_{\mathbf{p}}, \mathbf{e}_l \rangle}{\langle \mathbf{F} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l, \mathbf{e}_l \rangle} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l \quad (\mathbf{F}^* \text{ is the adjoint of } \mathbf{F}) \\ &= \mu_{\mathbf{p}} + \frac{1 - \langle \mu_f, \mathbf{e}_l \rangle}{\langle \Sigma_f \mathbf{e}_l, \mathbf{e}_l \rangle} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l \\ &= \mu_{\mathbf{p}} + \frac{1 - \mu_{fl}}{\Sigma_{fl}} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l \end{aligned} \tag{5.10}$$

$$\begin{aligned} \tilde{\mathbf{p}}^{(l,-)} &= \mu_{\mathbf{p}} - \frac{1 - \langle \mu_{\mathbf{p}}, -\mathbf{F}^* \mathbf{e}_l \rangle}{\langle -\Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l, -\mathbf{F}^* \mathbf{e}_l \rangle} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l \\ &= \mu_{\mathbf{p}} + \frac{-1 - \langle \mu_{\mathbf{p}}, \mathbf{F}^* \mathbf{e}_l \rangle}{\langle \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l, \mathbf{F}^* \mathbf{e}_l \rangle} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l \\ &\vdots \\ &= \mu_{\mathbf{p}} + \frac{-1 - \mu_{fl}}{\Sigma_{fl}} \Sigma_{\mathbf{p}} \mathbf{F}^* \mathbf{e}_l. \end{aligned} \tag{5.11}$$

By symmetry of the marginal distribution of f_l , it follows that in the unlikely case where μ_{fl} is zero, the line current is equally likely to deviate to the left as it is to deviate to the right, and both cases come with a different power injection. When μ_{fl} is non-zero, one of the two cases is more likely.

$$\begin{aligned} \mu_{fl} > 0 &\iff \tilde{\mathbf{p}}^{(l,+)} \text{ is the most probable injection,} \\ \mu_{fl} = 0 &\iff \tilde{\mathbf{p}}^{(l,+)} \text{ and } \tilde{\mathbf{p}}^{(l,-)} \text{ are the two most probable injections,} \\ \mu_{fl} < 0 &\iff \tilde{\mathbf{p}}^{(l,-)} \text{ is the most probable injection.} \end{aligned}$$

When $\mu_{fl} \neq 0$, we can use the sign function to combine Equations (5.10) and (5.11) into one, which gives the desired expression. 

Large dev: in het limiet $\epsilon \rightarrow 0$ valt de verwachtingswaarde van \mathbf{p} , gegeven emergent failure l , samen met de zojuist gegeven mode.

5.9 Redistribution of flow

In the previous section, we studied normally distributed power injections, and we can now discover which lines are likely to fail, and what power injection was the most likely

cause. The next step is to study the *redistribution of flow*: when overloaded lines are switched off (which happens almost instantly), the remaining lines in the network will have to take over their function, because *the power injection remains unchanged after a line outage*. In the simplest case of two parallel lines that connect two otherwise unconnected grids (say, a geographical island connected to the mainland via two cables), the failure of one line will force the other line to carry its original current, plus the current that would normally flow through the failed line.

Except for special cases like these, this *redistributed flow* is, in general, hard to compute without the tools developed in this section. The general case not only consists of all possible line failures, we also want to study all *possible combinations* of line failures.

We will discuss two methods to solve this problem: the Direct and the Optimised methods. The first method simply considers the graph obtained by removing the failed lines from the network, and then recalculates (LPF) for the network. Calculating the Moore-Penrose inverse of \mathbf{L} is computationally expensive¹¹, and every combination of line failures requires this calculation.¹² A second method, first introduced by ?, utilises the LPF of the original network to derive the redistribution of flow. This Optimised method is computationally less expensive, and provides additional insight into the effect of line outages, that would not be obtained when discarding the original network.

LODF matrix

5.9.1 Direct method

Eigenlijk is deze methode net al verteld. Misschien is dit een goede plek voor power islands?

For the Direct method, we simply recompute the LPF for the perturbed network. To avoid reducing the dimension m , and recalculating \mathbf{K} , we set the admittance of each failed line to zero.

More formally, suppose $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$ is an (n, m) -grid structure with $\mathcal{Z} \subseteq [m]$ a collection of $v \in [m]$ lines that fail. For an injection $\mathbf{p} \in \mathbb{R}^n$, the line flow

the line flows *before* the failures of \mathcal{Z} is given by:

$$\mathbf{f}^{\mathcal{Z}} = \text{diag}(i\boldsymbol{\eta})\mathbf{K}^* (\mathbf{K}\text{diag}(i\boldsymbol{\eta})\mathbf{K}^*)^+ \mathbf{p} \quad (5.12)$$

(by definition of \mathbf{F}) and the line flows *after* the failures are given by:

$$\mathbf{f}^{\mathcal{Z}} = \text{diag}(i\boldsymbol{\eta})\mathbf{K}^* (\mathbf{K}\text{diag}(i\boldsymbol{\eta})\mathbf{I}_{[m] \setminus \mathcal{Z}}\mathbf{K}^*)^+ \mathbf{p}, \quad (5.13)$$

where $\mathbf{I}_{[m] \setminus \mathcal{Z}}$ is the identity matrix, with diagonal entries set to zero for line numbers contained in \mathcal{Z} . By taking the product $\text{diag}(i\boldsymbol{\eta})\mathbf{I}_{[m] \setminus \mathcal{Z}}$, we are essentially setting the admittance of failed lines to zero, which corresponds physically to a circuit break.

¹¹Scientific computing libraries generally calculate \mathbf{L}^+ using the Singular Value Decomposition of \mathbf{L} .

¹²Calculating the LPF of the SciGrid network ($n = 489$, $m = 895$) takes approximately 700 ms, excluding the additional overhead of copying the unperturbed network.

5.9.2 Optimised method

Theorem 5.9.1. Suppose $((\mathcal{N}, \mathcal{L}), \mathbf{K}, \boldsymbol{\eta})$ is an (n, m) -grid structure, with LPF \mathbf{F} . Suppose that $\mathcal{Z} \subseteq [m]$ is a collection of $v \in [m]$ lines that fail. For a given injection $\mathbf{p} \in \mathbb{R}^n$, the line flows before the failures of \mathcal{Z} are given by:

$$\mathbf{f} = \mathbf{F}\mathbf{p} \quad (5.14)$$

$$(5.15)$$

and the line flows after the failures are given by:

$$\boxed{\mathbf{f}^{\mathcal{Z}} = \mathbf{f} - \mathbf{M}\mathbf{N}(\mathbf{N}^*\mathbf{M}\mathbf{N})^+ \mathbf{N}^*\mathbf{f}} \quad (5.16)$$

where $\mathbf{M} = \mathbf{F}\mathbf{K} - \mathbf{I} \in \mathbb{R}^{m \times m}$ and $\mathbf{N} = (\mathbf{e}_{\mathcal{Z}_1} \cdots \mathbf{e}_{\mathcal{Z}_v}) \in \mathbb{R}^{m \times v}$, the matrix that is zero everywhere, except for the entries (\mathcal{Z}_i, i) (for $i \in [v]$), where it has value 1.

Remark. This expression for $\mathbf{f}^{\mathcal{Z}}$ also contains a pseudo-inverse, which might not look computationally advantageous, compared to the Direct method. Note, however, that right multiplying by \mathbf{N} corresponds to taking the *submatrix of column numbers* \mathcal{Z}_1 through \mathcal{Z}_v , and left multiplying by \mathbf{N}^* gives the submatrix of *row numbers* in \mathcal{Z} . This means that \mathbf{M} only needs to be computed once, after which most matrix multiplications in (5.16) can be done by *indexing appropriately*, for any combination of line failures. Additionally, if the number of failed lines is small, the product $\mathbf{N}^*\mathbf{M}\mathbf{N}$ will be a small matrix, drastically improving performance. Lastly, this expression only requires (pseudo-)solving the system of equations $(\mathbf{N}^*\mathbf{M}\mathbf{N})\boldsymbol{\alpha} = \mathbf{N}^*\mathbf{f}$, which can be done more efficiently than computing the full pseudo-inverse. (The same optimisation can be also applied to the Direct method.)

Several proofs to this theorem exist. The first proof, by ?, iterates over the failed lines, proving the result by natural induction. (?) provide two additional proofs, which follow from a careful analysis of the Direct method, where they *remove the columns of \mathbf{K}* that correspond to failed lines. An entirely different, fourth proof, due to ?, uses the formalism of *graph cycles*, which form a basis for $\ker \mathbf{K}$. Their article is truly fascinating, as it explores how flow redistributions are composed of loop flows. Additionally, they derive a more general result, where the grid perturbation is expressed as a *change in line admittances $\boldsymbol{\eta}$* .¹³ Taking the limit $\eta_l \rightarrow 0$ then corresponds to the removal of the line.

Before providing this fourth proof, we will try to deduce the result from intuitive reasoning, to better understand the found expression.

Intuitive argument. Both \mathbf{f} and $\mathbf{f}^{\mathcal{Z}}$ are induced by the same power injection, i.e. $\mathbf{K}\mathbf{f} = \mathbf{K}\mathbf{f}^{\mathcal{Z}} = \mathbf{p}$. This means that the difference between the two, which is the change in flow right after the line failures, is an *element of the kernel of \mathbf{K}* . We denote this difference by $\Delta\mathbf{f} := \mathbf{f}^{\mathcal{Z}} - \mathbf{f}$.

For each $l \in \mathcal{Z}$, the current through line l must become zero. This imposes the condition

$$\Delta f_l = f_l^{\mathcal{Z}} - f_l = -f_l, \quad (5.17)$$

¹³Some transmission networks deploy adjustable inductors that clamp onto transmission lines, to steer the flow of current, making this generalisation especially relevant.

or more compactly,

$$\mathbf{N}^* \Delta \mathbf{f} = -\mathbf{N}^* \mathbf{f}. \quad (5.18)$$

Let us first consider the case of a single failure: $\mathcal{Z} = \{l\}$, that does not cause the network to become disconnected. We are looking for a $\Delta \mathbf{f} \in \ker \mathbf{K}$, under the condition that $\mathbf{f}_l^{\mathcal{Z}} = -\mathbf{f}_l$. The first choice that might come to mind is to fix a basis of $\ker \mathbf{K}$ consisting of *unit loop flows* in the graph. We can pick a unit loop flow that is non-zero at l , and scale by $\pm \mathbf{f}_l$ to find the desired flow difference.

Although this does satisfy the condition at l , it is in general not the flow that will be *induced* in the perturbed network, which is uniquely determined by power flow physics. There are many linear combinations of unit loop flows that satisfy the condition at l , one of which is the correct one.

Suppose that the network is unused ($\mathbf{p} = \mathbf{0}$), and we *force* a current of 1 through line l , and fix all other line currents to 0. This line flow vector is given by \mathbf{e}_l . The result of this flow will be a power injection which remains zero everywhere, except at the two nodes that $\mathcal{L}_l = (i, j)$ connects. This power injection is given by \mathbf{Ke}_l .

On the other hand, if we were to apply the injection \mathbf{Ke}_l to the network, allowing current to flow naturally, we would find the vector of line currents \mathbf{FKe}_l , which in general does not equal \mathbf{e}_l ! Of course, the natural line flow in l will still be relatively large, but some power will be transmitted along different routes. For example, in a circular network of four buses and four lines of equal admittance, with $l = 1$, we find¹⁴

$$\mathbf{FKe}_1 = \begin{pmatrix} 0.75 \\ -0.25 \\ -0.25 \\ -0.25 \end{pmatrix}, \text{ with difference } \mathbf{FKe}_1 - \mathbf{e}_1 = \begin{pmatrix} -0.25 \\ -0.25 \\ -0.25 \\ -0.25 \end{pmatrix}.$$

Because \mathbf{F} is the right-inverse of \mathbf{K} , we find that $\mathbf{K}(\mathbf{FKe}_l) = \mathbf{Ke}_l$, which means that the *difference between a natural flow and a forced flow*, $\mathbf{FKe}_1 - \mathbf{e}_1$, is an element of the kernel of \mathbf{K} .

We have not yet satisfied the condition (5.18). Given a power injection \mathbf{p} and unperturbed flow $\mathbf{f} = \mathbf{Fp}$, we can *scale* the above difference with some $\alpha \in \mathbb{R}$:

$$\Delta \mathbf{f} = (\mathbf{FKe}_l - \mathbf{e}_l) \alpha$$

with α such that

$$\Delta \mathbf{f}_l = -\mathbf{f}_l$$

is satisfied. If the network remains connected, α is given by $-\mathbf{f}_l / (\mathbf{FKe}_l - \mathbf{e}_l)_l = \mathbf{f}_l / (1 - (\mathbf{F}\mathbf{K})_{ll})$. We state, without proof, that this is indeed the flow difference dictated by power flow physics.¹⁵

Power island, pseudoinverse

Het voorbeeld van een circulair netwerk is te simpel

¹⁴The series combination of lines 2, 3 and 4 has a third of the admittance of line 1, so their current must equal a third of the current through line 1.

¹⁵If we assume the Theorem to be true, one could work backwards from (5.16) to find this result.

In the general case of multiple line failures, we essentially apply the above procedure to each failed line, and add the resulting differences. If we were to use this method *iteratively*, by considering the failed lines in some chosen order, we run into the following issue, when more than one line is removed: when removing the second line from the network, we will find a difference flow that sets the second line current to zero. Unfortunately, this difference flow will also change the current of the first line, which is then no longer zero. If we then consider the first line again, we will also affect the second line, et cetera.

To avoid this cat-and-mouse game, we need to find all scaling factors $\alpha_1, \dots, \alpha_v$ *simultaneously*. By virtue of linearity, the v conditions imposed by (5.18) form a set of *linear conditions* on $\alpha = (\alpha_1, \dots, \alpha_v)^*$.

For each line $l \in \mathcal{Z}$, the natural-forced difference is $\Delta f^l := \mathbf{F}K\mathbf{e}_l - \mathbf{e}_l$. When combining all differences for $l \in [m]$ as columns of a matrix, we find:

$$\begin{pmatrix} | & & | \\ \Delta f^1 & \dots & \Delta f^m \\ | & & | \end{pmatrix} = \mathbf{F}\mathbf{K} - \mathbf{I} = \mathbf{M}$$

The sub-matrix of differences for $l \in \mathcal{Z} \subseteq [m]$ is given by:

$$\begin{pmatrix} | & & | \\ \Delta f^{\mathcal{Z}_1} & \dots & \Delta f^{\mathcal{Z}_v} \\ | & & | \end{pmatrix} = \mathbf{M}\mathbf{N}$$

Note that $\mathcal{Z}_1, \dots, \mathcal{Z}_v$ do not need to be ordered.

A linear combination of $\Delta f^{\mathcal{Z}_1}, \dots, \Delta f^{\mathcal{Z}_v}$ with scale factors $\alpha_1, \dots, \alpha_v$ is given by

$$\Delta \mathbf{f}(\alpha) = \mathbf{M}\mathbf{N}\alpha. \quad (5.19)$$

Condition (5.18) then becomes:

$$\mathbf{N}^*\mathbf{M}\mathbf{N}\alpha = -\mathbf{N}^*\mathbf{f} \quad (5.20)$$

with pseudo-solution

$$\alpha = -(\mathbf{N}^*\mathbf{M}\mathbf{N})^+ \mathbf{N}^*\mathbf{f}. \quad (5.21)$$

Finally, combining (5.19) and (5.21) gives:

$$\Delta \mathbf{f} = -\mathbf{M}\mathbf{N}(\mathbf{N}^*\mathbf{M}\mathbf{N})^+ \mathbf{N}^*\mathbf{f},$$

in agreement with the result. 

The proof of Theorem 5.9.1 is given in ?. This only needs to be adapted to our notation.

Part II

Predicting failures in Germany's grid

Chapter six

Methods

The goal of the model described in this thesis can be summarised as follows:

Given:

- A real-world *grid structure*
- Hourly *load series*
- Hourly *generation series*

Predict:

- ‘*Top 10*’ of lines most likely to fail
- For each risky line: the most likely *cascading line failures*

The model, in particular the use of large deviation statistics to study cascading line failures, was proposed by Nesti et al. (2018a). Following their approach, the model is applied numerically to the SciGRID dataset (Matke et al., 2016). This dataset is an approximation of the transmission network in Germany, including grid structure, generation capacity, hourly load series and hourly renewable generation series.

As discussed in Section ??, transmission lines can fail for a number of reasons, and this model only studies one specific type of failure: *short-term changes in renewable generation*.

Line overloads are, however, the most imminent type of failure in a network, in the sense that grid operators need to continually monitor the *configuration* (distribution among the nodes of power generation) to ensure that no line will overload. This strongly constrains the capability of the transmission network. At any point in time, there could be many configurations that are environmentally (or *economically*) better than the current configuration, but they might lead to a line overload.¹ Turning off functioning

how common are these types of failures?

¹It is for this reason that the Optimal Power Flow problem is computationally difficult solve: it often takes many iterations until a generation distribution is found that does not cause any transmission line to be overloaded.

wind turbines is known as *wind curtailment*, and switching off solar panels is called *solar curtailment*.²

In China, as of 2019 the world's largest producer of renewable energy *by a factor of two*, wind curtailment amounted to 16% between 2010 and 2016. (Ye et al., 2018)

ref, wiki

compare to
european
consumption

6.1 Constructing a complete dataset

European grid operators have detailed datasets that describe the grid structure and state of the transmission network, but these are not (yet) publicly available. We use the work of Brown et al. (2018), which combines open datasets from different sources, to obtain an approximate representation of the German transmission network.

6.1.1 Grid structure

The *European Network for Transmission System Operators for Electricity* (ENTSO-E) was established in 2008 to promote the integration between the electricity markets of European member states, and to increase public transparency of these markets. ENTSO-E provides a number of public datasets, including historical hourly load series, international energy flows, and yearly generation series. An up-to-date map can be viewed, containing almost all high-voltage transmission lines in Europe, and lines outside of Europe that are part of the synchronous grid of Continental Europe. Unfortunately, this dataset is not available in a computer-readable format,³ and only gives the operating voltage and number of parallel circuits of a line.

Luckily, the SciGRID project has assembled an open source dataset of grid structure, using an entirely different source. The OpenStreetMap project is a detailed, open source world map, maintained by a community of mappers. The map is so detailed, in fact, that it not only contains most transmission lines and substations of Europe, it even contains observations of the number of parallel circuits, the number of wires per cable⁴, the frequency⁵, the name of the grid operator, the operating voltage⁶, and the names of the two buses that it connects. From these characteristics, line resistance and inductance can be estimated. The SciGRID dataset has aggregated OpenStreetMap data, and highly simplified the network, resulting in a complete grid structure.

²Wind turbines can indeed be turned off, by twisting the rotor blades towards 0° pitch and applying the *brakes*. In large turbines, common types are drum brakes (similar to a back-pedalling brake for bikes) and disk brakes. Brakes are especially important during maintenance. Solar panels are switched off using a simple mechanical or electronic switch (a relay). (Denholm et al., 2015)

³they provide a more on this later

⁴You can sometimes see that a cable is made up of three wires, with less than a metre of separation between them. This increases the total surface area of the cable with relatively low increase in volume (i.e. cost).

⁵which is always 50 Hz in Europe

⁶This can be deduced from the physical size of the insulators between the cable and the transmission tower (or you could ask the operator).

6.1.2 Grid state

For our analysis, we need the *hourly* generation series (for each generator at each node), and the hourly load series (aggregated at each node). This data is not publicly available. Yet, previous work (Brown et al., 2018) has shown that these values can be estimated for the German network by combining public sources, in particular:

- SciGRID, which is based on OpenStreetMap data, for the grid structure (as discussed above);
- Data published as part of the German Renewable Energy Sources Act (*Erneuerbare-Energien-Gesetz*), for the location and capacities of solar and wind sources;
- ? provide a world map of hourly solar and wind *potential*, based on weather data and forecasts, for hourly wind and solar series;
- Federal Network Agency of Germany (*Bundesnetzagentur*), for the location and capacities of all other energy sources;
- Global Domestic Product (GDP) and population density of districts (*Landkreise*) of Germany, for load sizes and locations;
- ENTSO-E hourly load series, for hourly load series.

We now have all the data that we need, except for the hourly generation series of *non-stochastic* energy sources. To fill this gap, Brown et al. (2018) use the clever solution of running an Optimal Power Flow (OPF) simulation for each hour, to determine the cheapest generator configuration. The rationale behind this method is that grid operators *use this exact method* to determine the hourly generator configuration. As long as the marginal costs of each generator are realistic, we hope to find a realistic generator configuration this way.

Clearly, the resulting dataset is an *estimation*, and any results that follow from it should be taken with a grain of salt. With this in mind, we proceed with our analysis, not necessarily with the goal of providing accurate operational advice for grid operators, but to demonstrate that the model can be applied to real-world transmission networks. In addition, we hope that this model will provide *qualitative insight* into the complex behaviour of grid failures.

Technical description of resulting dataset

6.1.3 PyPSA

context: PSAT for matlab Milano (2005), references 110 and 111 of PSAT manual
Milano (2013)

some example graphs

PyPSA:
Brown et al.
(2018)

Maybe:
PyPSA-
EUR:
Hörsch et al.
(2018)

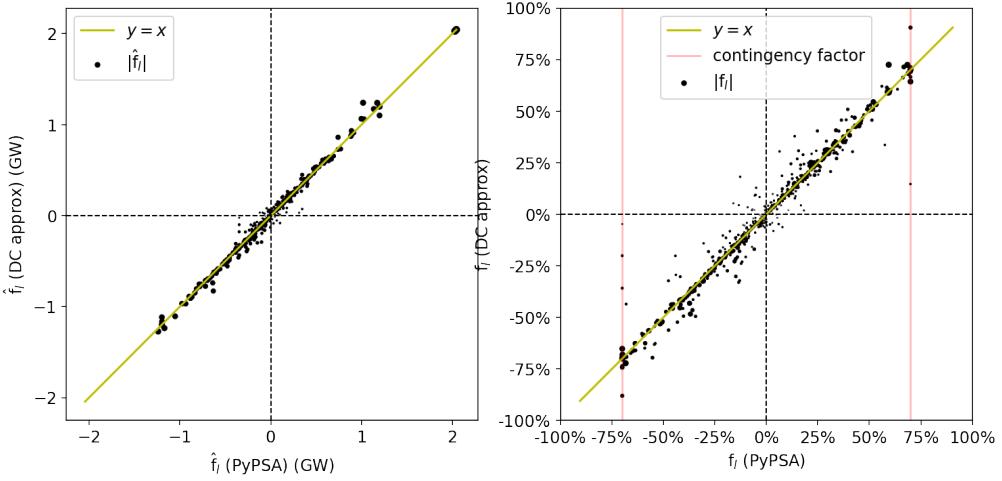


Figure 6.1: PLACEHOLDER: Line flow (left) and saturation (right) computed using LPF and (non-linear) PF.

6.1.4 A note on larger datasets

Although the full ENTSO-E network can only be viewed on their official website, Hörsch et al. (2018) were able to extract this information into a usable format. They provide the tools to construct a full dataset for European load en generation, but this process is too computationally demanding to take on in this thesis.

In fact, the limitation of our dataset does have a number of benefits. There are obvious computational benefits, which allow us to study the network without simplification,⁷ and the network is small enough for individual lines to be studied. One additional advantage is that the distribution of installed renewable generation is consistent within Germany (see Figure 7.7), while a European dataset would see large differences among countries (which all have different policies). Finally, Germany has the highest share of stochastic⁸ generation among European countries: in 2011, 41% of solar energy and 31% of wind energy in the European Union was generated in Germany.⁹

6.2 LPF

6.2.1 Comparison with PyPSA results

6.3 Stochastic power injection

6.3.1 Explorative data analysis

6.3.2 ARMA model

Computing ARMA fits

Following Nesti et al. (2018a), the ARMA models were fitted to the first month of solar and wind generation series using the arima method in R. This produced the desired result for all wind series.

Unfortunately, the arima method failed to fit an ARMA model for 104 of the 489 buses, reflecting the hypothesis that these series are poorly modelled by an ARMA series. To recreate the results of Nesti et al. (2018a), it is crucial that a model can be fitted for *every* bus. Therefore, a modified method is required.

By the default, the arima method operates in two steps. First, a so-called Conditional-Sum-of-Squares (CSS) method is used as initial guess for the ARMA coefficients. Then, the coefficient *likelihood* function is maximised with the Nelder-Mead optimisation method, using the CSS result as initial value.

In our case, the CSS method often finds initial values that are *non-stationary*. A define? possible reason is that solar generation is exactly zero during nighttime, which lasts for up to 16 consecutive hours.¹⁰ To resolve this issue, we use an optimisation method that works well without specifying an initial value: it should find the *global* maximum independently. The Simulated Annealing (SANN) algorithm included in R is such a method, and was chosen for this analysis.

With SANN as optimisation method, arima was able to fit solar models for 484 out of 489 buses. For the remaining 5 buses, a second technique is applied: to accommodate for the long periods of zero generation, a small amount of uniform noise is superimposed on the generation series. Initially, the noise magnitude is set to 1% of the solar capacity of the bus. This percentage is increased iteratively, until the modified method is able to fit a solar model. In fact, 1% noise proved sufficient for the remaining 5 buses in January, and no more than 2% noise was needed for any bus in the remaining months.

The modified method described in this section was used to fit solar and wind models to each bus of the network, for each month of 2011. Table 7.1 lists the number of buses that can be analysed using the default and modified methods, showing the poor performance of the default for solar series, especially during the months of summer.

define?

Belisle 1992,
zie optim
docs

⁷In larger datasets, the set of buses often needs to be clustered to solve the OPF problem.

⁸This does not include renewable deterministic generation, notably hydroelectricity.

⁹Sources: European Wind Energy Association and EurObserv'ER

¹⁰In reality, solar generation is never *exactly* zero, even after sunset, because solar panels also receive ambient light. This is not included in the (artificial) dataset.

Nesti et al. (2018a) do not mention such problems (nor techniques to solve them). Because the same dataset, processing, programming language and method was used in this analysis, it is likely that they have also encountered and solved these problems, possibly in the same manner.

discuss other possible techniques: warm start, intercept

Runtime

The default implementation has an estimated (single-core) runtime of 101 hours (4.2 days) when all 12 months are analysed, although only 78% of fits are successful using this method.

The modified version is able to fit all generation series successfully. The use of this more computationally expensive method increases the runtime to an estimated 224 hours (9.4 days). Because of the long runtime, fits were computed in parallel on a 40-core machine¹¹, provided by the IT department of the Radboud University.¹² This reduced the total runtime down to 7 hours. The results are publicly available at the GitHub repository.

6.4 Stochastic line flows

6.4.1 Line failures

6.5 Most likely power injection

The most likely power injection, given the failure of a line, was computed directly using Theorem 5.8.1. This method is numerically stable, even when the failure probability is, to numerical approximation, equal to 0. Furthermore, while the proof of Theorem 5.8.1 uses (the existence of) the inverse of Σ_p , it is not required in the final expression.

When examining the result of this calculation for a number of lines, we found two problems with the final result, which are more prominent when stable lines (those with negligible overload probability).

6.5.1 Non-zero net injection

First, the most likely injection might not have zero sum. We can safely apply the matrix F to an injection p that does not have zero sum. Nevertheless, under our assumptions, p must have zero sum. As part of the DC approximation, we found that the power injection is the image of $L = K \text{diag}(i\eta) K^*$, applied to the vector of phase angles, θ (Equation 5.6). From Theorem 2.3.6 it then follows that the power injection should have zero sum.

¹¹Specifications: two Intel Xeon E5 2630L v4 10-core processors @2GHz with hyperthreading; 64GB RAM. CPU time was used as estimate for single-core runtime.

¹²Thank you!

Instead of concluding that our model, and the results that follow, are therefore entirely invalid, we will simply *ignore this problem*. We do so with the same reasoning as Nesti et al. (2018a): in reality, the total power injection is never exactly of zero sum. As discussed in Section 4.3, turning any grid-connected device on or off will change the total injection. This does *not* cause the power grid to ‘promptly vanish in a puff of logic’, but rather, it physically causes a *change of AC frequency*. This change in frequency is then measured by grid operators and generators, who react by changing their energy output to compensate for the change in frequency. This feedback loop is *stable* (von Meier, 2006), as long as frequency changes are small, and the demand can be met.¹³

The generators (or rather, the buses that they are connected to) that respond to a change in AC frequency are called the *slack buses* of the network, and they are chosen by the grid operator. In our discussion of the energy market (??), we assumed, for didactic simplicity, that a single generator is assigned to be the slack bus.

Nesti et al. (2018a) assume, for mathematical simplicity, that all generators play this role, which is called *distributive slack*. The individual amounts of change in generation is chosen such that the line flows after all generators have settled into a zero-sum are exactly equal to $\mathbf{F}\mathbf{p}^{init}$, where \mathbf{p}^{init} is the initial, non-zero power injection. This redistributed injection is given by:

$$\mathbf{p}^{slack} = \mathbf{K}\mathbf{F}\mathbf{p}^{init}.$$

When \mathbf{p}^{init} does have zero sum, we find $\mathbf{p}^{slack} = \mathbf{p}^{init}$, since \mathbf{F} is the right-inverse of \mathbf{K} , when restricted to the set of zero-sum injections.

6.5.2 Unrealistic renewable fluctuations

The second problem with the most likely injection is that it might not be realistic, simply because there are not enough solar panels and wind turbines to produce the predicted injection. A simple way to check this condition is to calculate the predicted increase in renewable generation at each node, and compare it to the installed capacity.

In Nesti is duurzame opbrengst een som van stochasten, en dus kan de maximale capaciteit wel worden overschreden (de capaciteit is dan ‘een schatting van een gemiddelde bovengrens’ oid). We kunnen dus beter berekenen met hoeveel procent we de capaciteiten moeten rekken daarvoor. Verder is de data slechts een schatting van capaciteit.

6.6 Cascading line failures

¹³Note that this is a one-sentence simplification of the study of *grid stability*.

Chapter seven

Results

In this final chapter, we

7.1 SciGRID data

The SciGRID dataset needs to be translated into the language of our model. It contains more information than we need, and it is not yet in the desired format.

7.1.1 Structure

(*A more detailed analysis of dataset properties is available on the GitHub repository.*)

Before any processing, we find that the SciGRID network (obtained from PyPSA example code, the exact dataset used by Nesti et al. (2018a)) contains 585 buses, 1423 generators (of all sources) and 489 loads. It also contains 38 storage units (all are pumped hydroelectric), but these were excluded from our analysis.¹ There are 852 transmission lines in the dataset, at possible voltage levels 220 kV and 380 kV, and there are 96 transformers (between these two voltages). Transmission lines have per-kilometre estimates for admittance, from which the total admittance can be deduced.

Voltages

In our model, we *normalise* the grid voltage. To do so, we multiply all line admittances by the *square* of their operating voltages, after which all voltages can be assumed to be 1, and a unit of current is proportional to a unit of transmitted power. Of the 585 buses, 192 are part of one of the 96 *voltage pairs*: these are two buses at the same location, with the same name (except for the voltage suffix), connected via a transformer. By merging these pairs, we find 489 geographically unique buses, at normalised voltage. From now on, we will refer to these (possibly merged) buses as the buses of the network: $n = 489$, $\mathcal{N} = [489]$.

¹More specifically, they were used in solving the OPF problem, but their initial charge was set to zero.

Loads

There is exactly 1 load connected to each bus. In reality, there are of course thousands of loads connected to a bus, but the load in the dataset is the *aggregated* load at that bus. We have hourly time series (i.e. amount of MW being consumed) for each node in the year 2011, which only includes active power consumption.

Generators

Generators are connected to the geographically closest bus, and there is at most one generator per bus of each type.² This means that generation is *aggregated*: multiple generators of the same type are combined into one. There are 489 solar generators, 488 onshore wind generators and 5 offshore wind generators. Offshore wind generators are connected to buses at the north coast of Germany. This means that every bus houses stochastic generation. Their geographic distribution is shown in Figure 7.7.

Lines

Line voltages and admittances are normalised as described above. For each line, we have the names of the two original buses that it connects, which can easily be converted to the new bus collection.

During the study of cascading failures, we found that the network contains *parallel lines*: lines that connect the same pairs of buses. In some cases, there are up to four different lines that are all parallel. When examining these cases on OpenStreetMap, we find that there are indeed parallel lines in the physical network. This is reflected by the *lengths* of parallel lines, as given by SciGRID: these are not the great-circle distances between buses, but rather the distance measured along the line (which makes some turns and bends).

Because our model only holds for *digraphs*, which cannot have parallel lines, we *combine* parallel lines, by summing their (voltage normalised) admittances, and summing their thresholds.³ Nesti et al. (2018a) do not mention this anomaly, and use the original set of lines. For comparison, we computed some results for both versions of the network, and found the results to be somewhat similar, in general. Because we did not consider the case of parallel lines in our model, combining parallel lines in the dataset seems like the *correct* choice.

Of the 852 original lines, there are 705 unique links between original buses before normalising voltages, and there are 695 unique links between buses. There are never two parallel lines with opposite orientation. These 695 lines were used in our model, and will be referred to as simply the *lines* of the network: $m = 695$.

²In order of installed capacity: *Wind Onshore* (37 GW), *Solar* (37 GW), *Hard Coal* (25 GW), *Gas* (24 GW), *Brown Coal* (21 GW), *Nuclear* (12 GW), *Run of River* (4 GW), *Other* (3 GW), *Wind Offshore* (3 GW), *Oil* (2.7 GW), *Waste* (1.6 GW), *Storage Hydro* (1.4 GW), *Multiple* (0.15 GW) and *Geothermal* (32 MW).

³The results regarding the kernel of K, and the Optimised method for analysis cascading failures, break down without this property.

7.1.2 State

Our dataset contains hourly values for load and stochastic (wind and solar) generation for the year 2011. Deterministic generation is estimated using the OPF algorithm, as implemented by PyPSA (Brown et al., 2018), a Python package designed for this purpose. Following common practice, we first multiply all line thresholds by a *contingency factor*: 0.70. This forces the optimisation process to leave a safety margin at every line, and also accounts for the error of using the DC approximation. Figure 7.1 shows the resulting injection at 1 January 2011 at 11:00. Line currents can then be computed using the LPF.

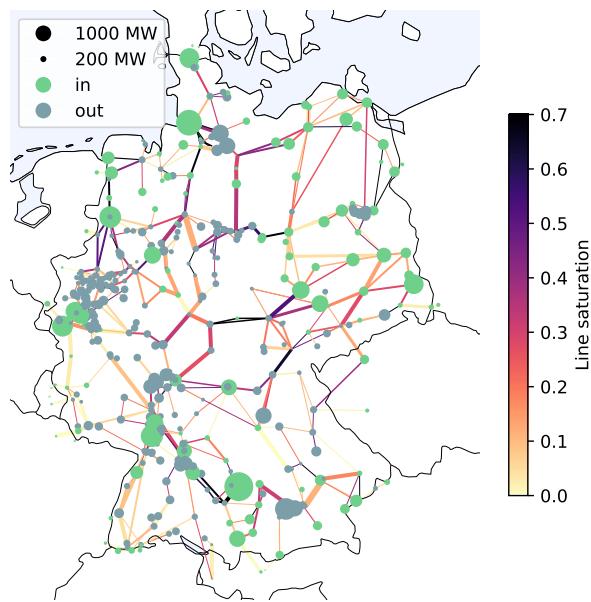


Figure 7.1: Nominal line flow during 11:00-12:00, as fraction of line capacity. Node size represents net power injection. When generation exceeds load, the injection is positive (green), otherwise negative (greyish blue). *Compare with Figure 1a of Nesti et al. (2018a).*

7.2 Bus covariance

We discussed two alternatives to estimating the covariance matrix directly from generation series: the covariance of ARMA residuals and the covariance of difference series.

7.3 Line covariance

By incorporating bus covariances in our model (which result from correlated weather), we hope to find new structure in the line covariances. To assess the effect of estimating bus covariances, we compare three possible bus covariance matrices:

	SOLAR				WIND			
	<i>default</i>	<i>modified</i>	1%	2%	<i>default</i>	<i>modified</i>	1%	2%
Jan	385	484	5	0	488	488	0	0
Feb	364	485	4	0	487	487	0	1
Mar	334	475	14	0	487	487	1	0
Apr	211	477	11	1	488	488	0	0
May	189	473	16	0	467	467	21	0
Jun	255	481	8	0	480	480	8	0
Jul	292	485	4	0	488	488	0	0
Aug	179	478	10	1	488	488	0	0
Sep	259	472	16	1	487	487	1	0
Oct	263	480	9	0	488	488	0	0
Nov	290	472	17	0	486	486	2	0
Dec	317	482	7	0	486	486	2	0

Table 7.1: Number of buses (out of 489 solar, 488 wind) for which the ARMA model could be fitted using either the *default* implementation of arima in R, or the *modified* version (described in 6.3.2).

When even the modified method yielded no results, uniform noise was added to the series before fitting. Noise magnitude was set to 1% of generation capacity, or 2% when needed.

Figures in **bold** indicate which results are used.

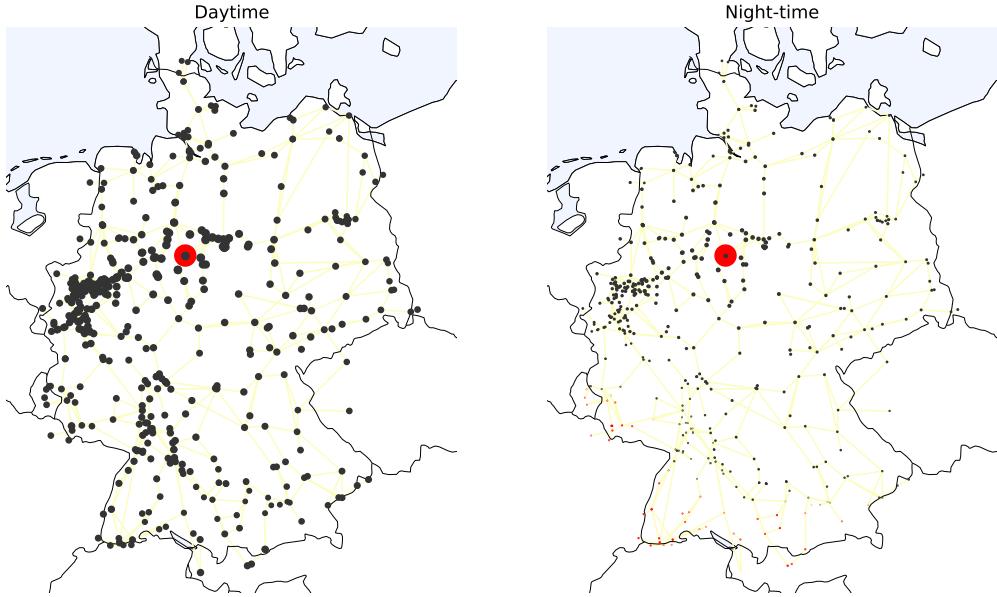


Figure 7.2: Covariance of all buses, relative to the circled bus. Normalised using installed renewable capacity.

1. *The identity matrix*: all bus injections are independently Gaussian distributed with the same variance. (They are almost IID, but their means differ.)
2. *The diagonal of estimated variances*: all bus injections are independently Gaussian distributed, but their variances and means differ.
3. *The estimated covariances*: the vector of bus injections is (multivariate) Gaussian distributed. All bus injections are, in general, dependent on each other, and their variances and means differ.

It is well known that local changes to the grid structure have long-range effects. For example, ? showed that *adding* a new line to a heavily congested, but stable network can cause the failure of another line, possibly far away from the added line.⁴ This is reflected in our model by the fact that line currents have non-zero covariance, even when bus injections are independently distributed. (In this case, $\Sigma_f = \mathbf{F}\mathbf{I}\mathbf{F}^* = \mathbf{F}\mathbf{F}^*$, which is generally not a diagonal matrix.) Figure 7.4a and Figure 7.4b show the covariances of all lines, relative to a chosen line. We see that covariance is generally high for lines that are close, but there are some clear exceptions. There seems to be a general trend that lines are highly (positively or negatively) correlated when they are close, and *oriented in the same direction* (e.g. East-West) as the chosen line.

The covariance of a random pair of lines is relatively high, when their physical separation (measured either in kilometres or in graph distance) is low. Because weather is correlated, even at high distance, using the bus full covariance might result in higher

⁴The counter-intuitive fact that adding a line, or increasing the impedance of existing lines, can make a network *more* congested, is known as *Braess' Paradox*. Similarly, some line failures can be prevented by switching off other lines in the network. See Figure 7.3 for a minimal example.

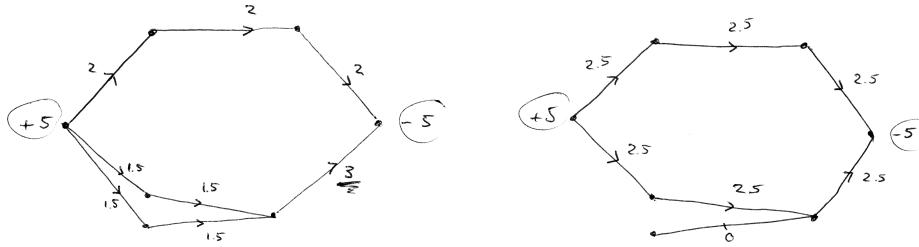


Figure 7.3: PLACEHOLDER: An example of Braess' Paradox. A network transporting 5 units of power from left to right; all lines have the same admittance, and threshold 3. On the left, one line (lower right) is overloaded. When this line fails, all power will travel through the upper branch, causing it to overload as well, leaving the network disconnected. If instead, the *lower left* line is switched off, the flow of power will be more evenly distributed, and no line will overload. Of course, this example also illustrates how adding a line could lead to overloads.

covariances between lines with high separation. (This was concluded by Nesti et al. (2018a).)

Using a different bus covariance matrix will likely result in a overall increase or decrease of line covariances. Note, however, that the line covariance matrix is scaled by an arbitrary factor ϵ , so any overall change in covariance has no significance in the model.

This makes it difficult to compare the three bus covariance matrices, as any absolute difference in line covariance should be ignored. Instead, we will examine the covariance of two lines, *relative to their own variances*. This way, the effect of any absolute, proportional increase in covariance is avoided. First, let us choose a number of lines, and examine the covariances of all other lines with the chosen line, relative to its variance.

In particular, we are interested in the decay of covariance over distance. ? studied the decay of the Line Addition Distribution Factor (difference in flow after adding a line) over distance, also using the SciGRID network. This is not the same as covariance, of course, but both are measures of the *global effect* of local changes in flow. They first determined the largest 2-connected component of the network, and removed all other lines from the model. In the remaining network, they studied the 880 possible additions of short new lines, and found a general *exponential* decay of change in currents as a function of graph distance.

To study the decay of covariance, we collect the geographical separation and covariance (resulting from the three possible bus covariance matrices) of 10^5 random pairs of lines in the network. Because of power flow physics, these covariances are highly spread out. However, when averaging the covariances in groups of 25 km (Figure 7.5), we find are able to see the differences in decay.

Outage

Compare three bus covariance

Maar als je normaliseert op variantie?

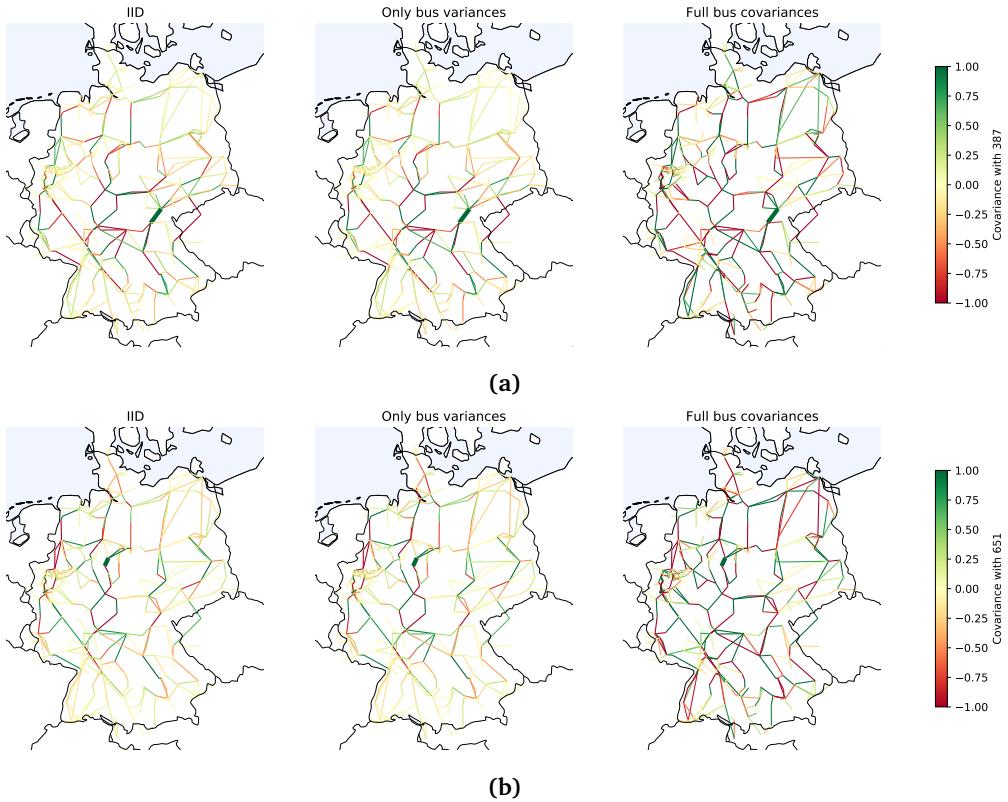


Figure 7.4: Covariance of all lines, relative to the enlarged line. Normalised using installed renewable capacity. Signs (red or green) can be chosen arbitrarily. Absolute covariance is therefore proportional to color *saturation*.

7.4 Most vulnerable lines

Using the nominal injection at 1 January, 11:00, we compute the failure probability of each line. The 20 most vulnerable lines are given in Table ??, and their positions are given in Figure 7.8. We identify the same vulnerable lines as Nesti et al. (2018b), but the ranking is different. This can be attributed to two differences in approach. First, we have combined parallel lines,⁵ which changes the vulnerability order significantly. It is unclear why this changes the result. For comparison, the ranking that we get *without* combining parallels is given in Table 7.2, which is more similar than that of Nesti et al. (2018b). The second major difference is the use of a different covariance matrix, although it is reassuring to see that the same lines are identified.

Check hun
cov

7.4.1 Cascades

In addition to the failure probability, we compute the most likely injection to cause that failure, and simulate the resulting cascade. The number of lines that either failed jointly with the initial failure, or failed during the subsequent cascade, is also given in

⁵all 20 most vulnerable lines were not part of a parallel combination

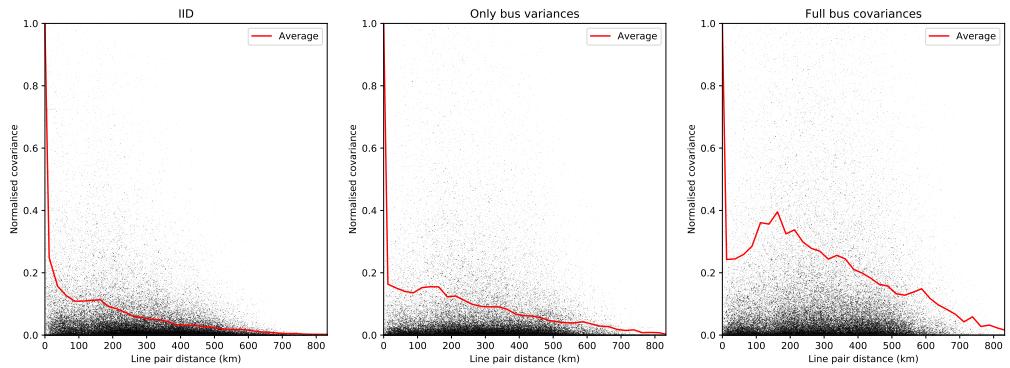


Figure 7.5: For 10^5 random pairs of lines, the covariance and distance (between line centres) is shown, for three possible bus covariance matrices. The averages (over 25 km) show that correlated buses increase long-range correlations in line flows. Covariances are normalised using average line variance.

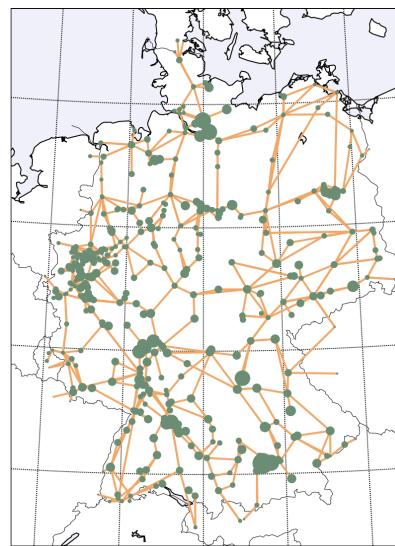


Figure 7.6: PLACEHOLDER: The load distribution of Germany at ???.

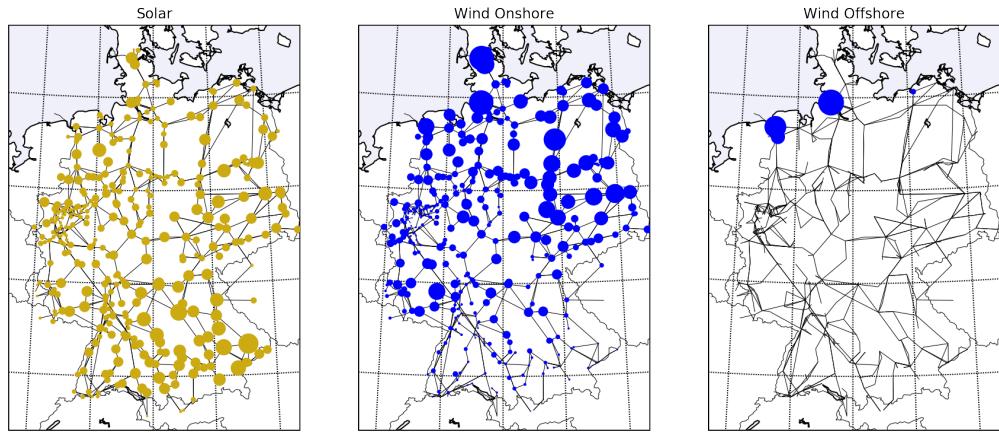


Figure 7.7: PLACEHOLDER: Solar, wind onshore, wind offshore generation at ?? in Germany.

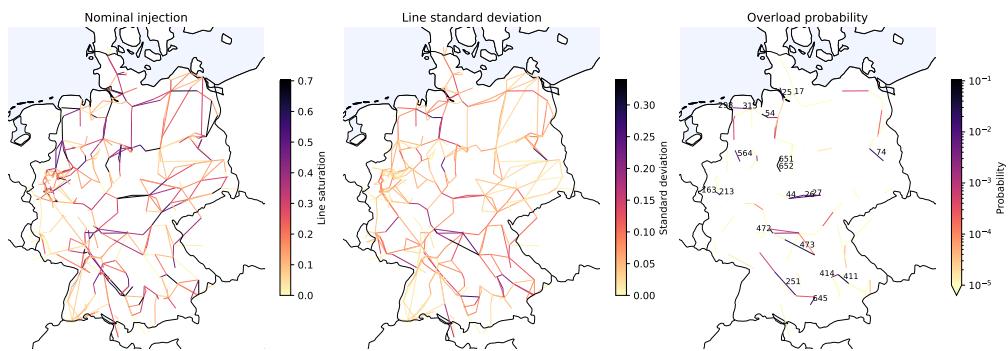


Figure 7.8: Visualisation of μ_f , Σ_f and $(\mathbb{P}[|f_l| \geq 1])_{l \in [m]}$ at 1 January, 11:00. The 20 most vulnerable lines are labelled.

Table ???. This extends the result of Nesti et al. (2018b), which only provides the failure probability.

We find that among the 20 most vulnerable lines (at 11:00),
geef percentage dat oke blijft

Using the most likely injection

hoe zijn de resultaten anders wanneer we niet de mli nemen?

7.4.2 Evolution of line vulnerabilities

Of course, the method above can be applied to any nominal injection, not just the injection at 1 January, 11:00. By applying the method to every hour of the first day, we find 24 different rankings, one of which is given in Table ???. This allows us to not only identify lines that are vulnerable at a given point in time, but to find lines that are a *consistent vulnerability*, based on the general use of the transmission network.

Instead of providing 23 additional tables, we have summarised the results of a full day in Figure 7.9. Here, we see that some lines (like 337) are only vulnerable at one point during the day, while others (298 and 54) have a consistently high overload probability. There is a clear distinction between daytime and night-time, since the time of day determines which covariance matrix is used in the calculation. In fact, this highlights how a change in covariance influences results: some lines are only vulnerable because of the covariances brought upon by solar generation, while others are relatively unaffected.

A most striking result is that the overload probabilities of 25 and 298 are perfectly *constant* for sustained periods, and both are likely to cause a cascade, resulting in an average of 108 and 76 failures, respectively. When examining these two lines in more detail, we find that both are *branches out of the network towards coastal cities of the North Sea*, with high-capacity offshore wind generation. These generators were operating at full capacity during the studied day,⁶ which would cause a constant⁷ power injection. Because the lines are *branches* out of the larger graph, the flow through the line is exactly equal to the power injection at its end, and therefore constant.

Regarding the subsequent cascades of these two lines, it seems like our model falls short of giving an accurate redistribution of flow, due to the singularity caused by their removal. (No flow redistribution exists that would not change the injection.)

7.5 Lines vulnerable to cascades

⁶according to our dataset

⁷except for the local energy usage, which is relatively small

l	$\mathbb{P}[f_l \geq 1]$	I_l
361	3.45 %	1.65
516	2.91 %	1.79
586	2.75 %	1.84
587	2.73 %	1.85
803	2.02 %	2.10
670	1.21 %	2.54
19	1.13 %	2.60
302	1.08 %	2.64
48	1.03 %	2.68
554	0.974%	2.73
488	0.971%	2.73
809	0.824%	2.88
28	0.748%	2.96
810	0.728%	2.98
29	0.396%	3.53
27	0.355%	3.62
389	0.247%	3.95
390	0.245%	3.96
486	0.235%	4.00
249	0.056%	5.30

Table 7.2: TODO

7.6 Previous work

This thesis was inspired by Nesti et al. (2018a), and we have verified their results. Our results are in overall agreement, with some minor differences.

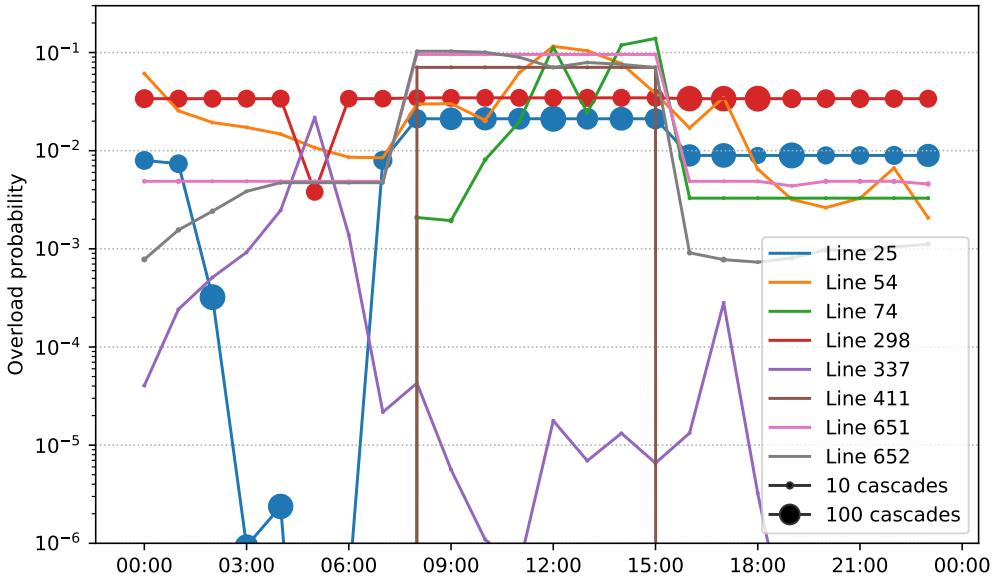
Verschillen:

- lijnen samengevoegd
- geen arma maar diff
- cascades gegeven van top 10

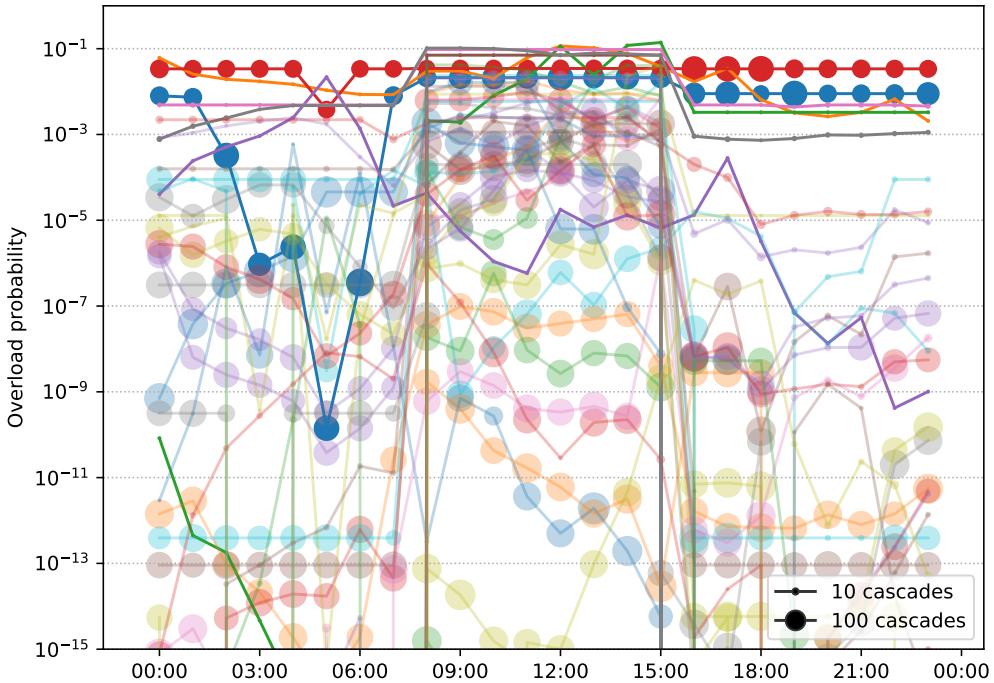
minder beknopt

Kritiek op nesti:

- ARMA modellen, logisch? nodig? goede modellen?
- geeft cascades niet van top 10
- ze nemen een contingency factor van 0.7 bij de OPF (arbitrair) maar voor de analyse van cascades niet. (toch?)



(a) All lines that are, at any time during the day, among the 3 most vulnerable lines.



(b) All lines that are, at any time during the day, among the 20 most vulnerable lines.

Figure 7.9: Evolution of absolute failure probabilities during 1 January 2011. Dot sizes represent final number of lost lines after the most probable cascade.

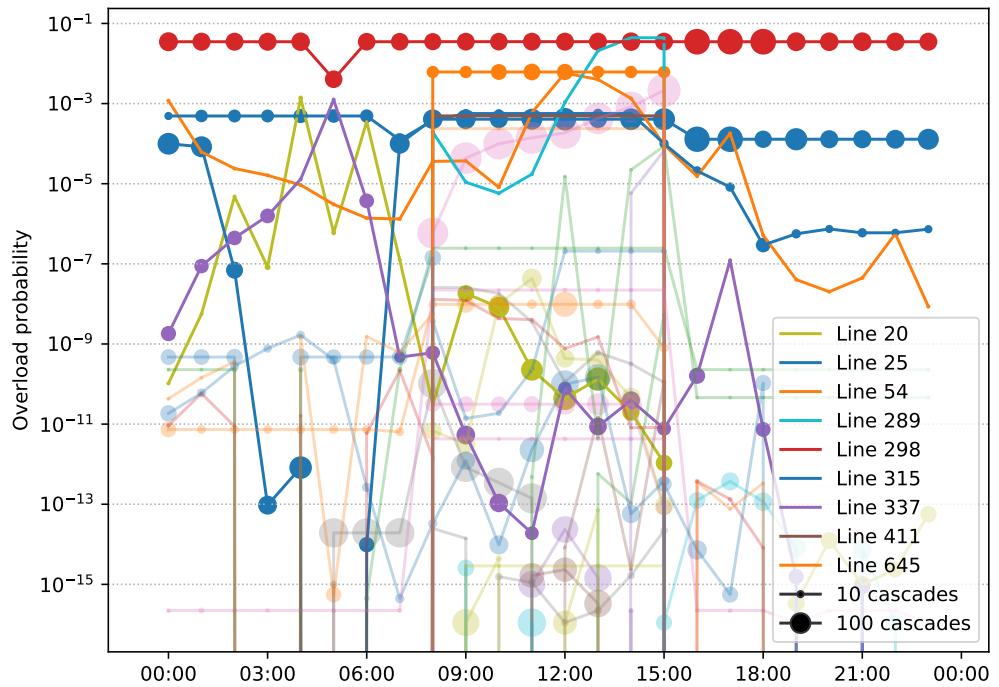


Figure 7.10: For reference, the same as Figure 7.9b, but computed using *uncorrelated* injections.

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