Power Grid Resilience to High Impact Low Probability Events

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Abstract
Forsberg, S. 2023. Power Grid Resilience to High Impact Low Probability Events. 54 pp. Uppsala: Uppsala University.

The electrification of societies and the decarbonisation of electricity production are changing energy systems worldwide. A fast transition towards the replacement of fossil fuels by intermittent renewable energy sources is expected in the next decades to combat climate change. A significant share of the produced electricity is likely to be generated from offshore wind farms, due to the abundant wind resources in the offshore regions and the lack of available onshore sites. However, increased electricity dependence in combination with expanded offshore wind power generation introduce new vulnerabilities to the society. Specifically, the effects of high impact low probability (HILP) events are considered as potential threats to the power system, not least because of the increasing number of extreme weather events. Therefore, research on power grid vulnerability and power system resilience to HILP events are of significant interest.

This thesis presents results of studies investigating power grid vulnerability from a topological perspective, and resilience to storm conditions of power systems with varying dependencies on offshore wind. To achieve this, methods based on complex network theory and AC power flow analysis have been developed, tested, and evaluated. Further, geospatial wind data from historical extreme storm events have been used to generate realistic power production profiles from hypothetical offshore wind farms.

The results strengthen that complex network concepts can be used successfully in the context of power grid vulnerability analysis. Further, the results show that the resilience of power systems with large dependencies on offshore wind differ vastly depending on the grid properties and control strategies, which are further discussed in this thesis.

Keywords: Extreme weather, HILP events, offshore wind, power grid, resilience, vulnerability

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To the Forsberg family.
Proverbs 3:5-6

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I. **Forsberg, S.**, Thomas, K., Bergkvist, M. (2023) Power grid vulnerability analysis using complex network theory: A topological study of the Nordic transmission grid. *Physica A*, 626:129072

II. **Forsberg, S.**, Thomas, K., Bergkvist, M., Göteman, M. (2023) Resilience to storm conditions of power systems with large dependencies on offshore wind. *Proceedings of the EERA DeepWind Conference*, January 18-20, 2023, Trondheim, Norway. To be published in *Journal of Physics: Conference Series* during autumn 2023.

III. **Forsberg, S.**, Göteman, M., Thomas, K., Bergkvist, M. (2023) Resilience to extreme storm conditions: A comparative study of two power systems with varying dependencies on offshore wind. Submitted to Energy Reports, 2023.

Contents

List of abbreviations

AC	Alternating current
FDXB	Fast decoupled power flow solver (XB version)
HILP	High impact low probability
HVDC	High voltage direct current
TSO	Transmission system operator

List of symbols

a	Hellman exponent
A_{vi}	The number of direct connections between node *v* and *i*
$C_B(v)$	Betweenness centrality of node *v*
$C_C(v)$	Closeness centrality of node *v*
$C_{comb}(v)$	Combined centrality of node *v*
$C_D(v)$	Degree centrality of node *v*
C_p	Aerodynamic performance constant
d_{ij}	Distance between node *i* and *j*
E	Set of edges
e_{ij}	Edge between node *i* and *j*
G	Graph
N	Number of nodes in a network
n_{ij}	Number of steps between node *i* and *j*
n_{rand}	A randomized number
P	Relative rated power output
P_{rated}	Rated power output
R_b	Wind turbine blade radius
l	Length of a transmission line
U	Wind speed
U_{100}	Wind speed scaled to an altitude of 100 meters
U_{cutin}	Cut-in wind speed
U_{cutout}	Cut-out wind speed
U_{ij}	Voltage level of transmission line between node *i* and *j*
U_{rated}	Rated wind speed
U_{ref}	Reference wind speed
V	Set of vertices
v_i	Vertex *i*
W	Set of weights
w_{ij}	Weight of link between node *i* and *j*
X_{ij}	Series reactance of transmission line between node *i* and *j*
x_{ij}	Series reactance per length unit between node *i* and *j*
z_{ref}	Reference height above ground of wind speed measurement
ρ	Air density
σ_{st}	Number of shortest paths between node *s* and *t*
$\sigma_{st}(v)$	Number of shortest paths between node *s* and *t* passing node *v*

1 Introduction

To reach the targets on reduction of fossil fuels to combat climate change, a fast transition to renewable energy sources is needed. To achieve this, increased electrification of the society is considered as a key factor. However, an increased electrification also implies an increased dependency on a reliable electrical power system. Already today, the electrical power system has a determinant role in the security, safety, economy, health, and well-being of societies which makes the electrical power system a critical infrastructure [1]. This dependency is expected to increase even more in the future.

Higher demands on a reliable electricity supply, an increased share of renewable energy sources, and an overall increased need for electricity introduce new challenges for the power systems. To tackle these challenges, major investments are planned in power system infrastructures globally. In Sweden, major reinvestment projects as well as new investments are planned to take place in the next decades, initiated by the transmission system operator (TSO) Svenska kraftnät [2]. One of these projects, called NordSyd, is the biggest power grid investment project in modern Swedish history, estimated to cost about $7 billion USD.

The increased electrification and replacement of fossil fuels by renewable energy sources are transforming the energy system worldwide. In the near future, a large share of the energy mix is expected to be provided by wind energy. The European Wind Association expects that 320 GW of wind generation capacity will be integrated into the European power system by 2030 [3]. Though, the available wind farm sites on land are limited. Further, the more abundant energy resources are available in the offshore regions. Therefore, offshore wind farms have gained interest among governments and private companies in recent years. The installed offshore wind power capacity is already increasing rapidly, with a cumulative power capacity of 27.2 GW in 2019 which corresponds to a growth of 24% compared to 2018 [4]. Another 29 GW of installed offshore wind power capacity is expected in Europe during 2022-2026 [5].

The intermittent nature of renewable energy sources such as offshore wind power, together with an increased electrification, introduces new vulnerabilities to the society. The vulnerability to high impact low probability (HILP) events, specifically storm conditions, can both be explicit and implicit; explicit in terms of physical damage to power grid components, and implicit in terms of reduced power generation due to wind speeds exceeding the cut-out wind velocity. Already today, extreme weather events and other HILP events are causing disruptions in power grids leading to power outages for millions of people [6]. The challenges are expected to increase even further caused by a rise in extreme weather events, both regarding frequency and intensity, due to climate change [7].

With an increased dependency on offshore wind, concerns are raised on how this can affect the resilience of power grids subject to extreme weather events. Further, the increased societal dependency on electricity urges for methods that can be used to identify power grid vulnerabilities, and thereby mitigate the consequences of HILP events. Even though there exists much research related to resilience of power grids subject to extreme weather events, the specific conditions and the degree of resilience differ significantly. Moreover, the practical applicability of complex network concepts in the context of power grid analysis is still open to debate. Thus, this thesis contributes to the existing research by filling these knowledge gaps.

In this thesis, power grid vulnerability and resilience are reviewed from two different perspectives. Firstly, the power grid vulnerability is presented from a topological perspective using complex network concepts, based on **Paper I**. Secondly, the power grid resilience is considered from a power flow perspective, focusing on possible power outages resulting from offshore wind farms shutting down due to cut-out wind speeds, based on **Paper II** and **Paper III**.

1.1 Aim of the thesis

The overall purpose of the thesis is to develop, test, and evaluate methods to quantify the vulnerability and resilience of power systems subject to HILP events. This is done by taking two different approaches into account, a topological and a power flow approach. More specifically, three aims are addressed and answered in the appended papers. These aims are:

I. Develop, test, and evaluate methods, based on complex network theory, to quantify the structural vulnerability of a model representing a real power grid.

II. Quantify the resilience of a power system with large dependency on offshore wind, subject to extreme weather events, by using a power flow based method.

III. By comparing two power system models with large dependencies on offshore wind, identify and evaluate parameters affecting the resilience of power systems subject to extreme weather events.

1.2 Overview of the thesis

The thesis is structured as follows: in Chapter 2, a review of the background is given. In Chapter 3, the methodology and data used in the appended papers are presented. The main results are given in Chapter 4 followed by a discussion and proposals for future work in Chapter 5. Finally, the thesis ends with Chapter 6 where the conclusions are summarised.

2 Background

In this chapter, the background of the thesis is presented. Firstly, related work on power grids as complex networks is reviewed in Section 2.1. Secondly, previous research on power grid resilience to extreme weather events are presented in Section 2.2. Then, the NordSyd project initiated by Svenska kraftnät is reviewed in Section 2.3, followed by a presentation of historical extreme weather events in Section 2.4. The chapter ends with the definitions of vulnerability and resilience in Section 2.5.

2.1 Power grids as complex networks

A power grid consisting of transmission lines and substations can be described as a network, containing nodes and links. To study the properties of such a network, complex network theory can be used. The concepts of complex network theory have been used extensively in power system research reaching a significant scientific impact [8–31]. However, even though the scientific impact is substantial, the practical applicability in the context of power system analysis is still open to debate [1,32–34]. Within the area of complex network research, two approaches have been formed: the purely topological and the hybrid approach. In the paragraphs below, a review of previous research on power grids and complex networks is presented. The text is from **Paper I**.

In [16], the Nordic transmission grid as well as a synthetic representation of the western USA transmission grid were studied with respect to the structural vulnerability of the systems, using a complex network theory approach. The grid consisted of undirected and unweighted edges which represented the physical structure of the power grid. Thus, the study is purely topological without any electrical dimensions taken into consideration. The paper presents results in terms of degree distributions, average clustering coefficient and average path length of the systems. It also examines the error and attack tolerance of the different grid models. Further, [20] examined the robustness of two power grid models, IEEE300 and a randomly generated 1000-node model. The study applied a combination of analytics, ranging from a purely topological perspective to an artificial flow model as well as a DC power flow model. The study showed that a combination of different approaches seems promising when evaluating the structural robustness of a power grid model.

Furthermore, in [35] and [36], the purely topological measures have been adjusted to fit the examination of electrical power systems. In these studies, the resistance and impedance of the cables and overhead lines have been used as the weighting factors, respectively. The vulnerability of the IEEE-30 and IEEE-118 models were assessed in [37] by applying complex network concepts where the edges were weighted with respect to the power lines' reactance values. In [38], the structural vulnerability of the Indian transmission grid and three generic IEEE models were investigated by applying both a weighted and an unweighted approach aiming to identify critical buses and transmission lines. For these grid models, a weighted approach gave more realistic results than the unweighted approach. The betweenness and netability were investigated for the IEEE-14 model in [27] in order to exhibit the critical lines in the model. To weight the edges with parameters capturing the physical properties of a power grid have been used extensively in the field of research.

2.2 Power grids subject to extreme weather events

Extreme weather and other HILP events can cause serious damage to the power system, resulting in power outages and destroyed infrastructure. Since the society is highly dependent on a stable and well-functioning power system, the performance of power systems subject to extreme weather conditions is an important field of research. Some of the research on power systems subject to extreme weather events is reviewed in this section. The text is from **Paper II** and **Paper III**.

In [39], the authors studied the resilience of an IEEE-RTS24 node grid with power generated by offshore wind farms, hydropower plants, and nuclear power plants during a typhoon event, and proposed an improved curtailment strategy to avoid severe power shortages and reduce the operational costs. Repair costs and capacity loss in the Texas power system, subject to hurricane wind conditions, was studied in [40]. It was seen that when the penetration increases from today's level of 20% to 80%, the system become more vulnerable to hurricanes. In [41], the vulnerability of the same Texas power system was studied in a situation with 3 large wind farms of a total of 317 wind turbines. Fragility curves of the wind turbines were combined with Monte-Carlo simulations to assess the probability of component failures due to the wind loading. All simulations resulted in a disconnected graph for the grid, highlighting the vulnerability in the system to external weather hazards.

In [42], the authors assessed hurricane generated loads on offshore wind farms in New England. A combined wind-wave model was first validated with data from the 2012 Sandy Hurricane, and then used to reproduce the most severe hurricanes recorded in the area: the 1938 hurricane and the 1954 hurricane Carol. Both were seen to represent extreme wind speeds with a 500-year return period. The wind and wave loading were used to model the structural response of a 5 MW offshore wind turbine in parked condition. It was seen that the results were sensitive to the input loads, concluding that the prediction of wind turbines to extreme weather conditions is associated with large uncertainties. Four potential wind farm sites in Mexico were considered by the authors in [43]; two in the Pacific Ocean and two in the Gulf of Mexico on the Atlantic side, and aimed to quantify the potential hazard posed by tropical cyclones. Assuming threshold for cut-out and failures, and investigating measured wind data at the four locations, they concluded that Category 4 and 5 hurricanes have the potential to cause periods of low power generation due to wind speed cut-out at all four sites. However, the likelihood of cut-out conditions occurring simultaneously at the four geographically separated sites was found to be very low.

In the high-fidelity numerical simulations of wind turbines subject to extreme wind loads in [44], it was concluded that design standards for wind turbines are exceeded in category 5 hurricanes, which causes concerns as many sites proposed for wind farm installations are in hurricane-prone regions. In addition, the vulnerability of offshore wind turbines to extreme weather conditions is expected to be higher than of onshore turbines [45]. Structural reliability analysis of wind turbines is often carried out using very simplified models for the structure and/or loading, and the results are equipped with large uncertainties, in particular for novel technologies [46,47].

The New England grid and wind turbines were also considered in [48], but this time from a market perspective; the authors assessed the electricity prices and related risks due to wind power losses during extreme winter storms in New England. They found that, despite price spikes occurring during winter storms cut-out wind speeds, even larger price spikes occurred during summer months due to low wind speeds and electricity production, in correlation with high power demand for cooling purposes. An economical perspective to resilience was also taken in [49], where the resilience of offshore wind farms was studied as a function of failures of wind turbine components, resulting both from extreme wind and wave loads, and due to constant failure rates. Preparedness to disturbances was seen to be a key factor to obtaining resilience of the system.

2.3 NordSyd project

Between 2016 and 2018, the Swedish TSO Svenska kraftnät performed a major system analysis of the Nordic transmission grid, focusing specifically on the Swedish transmission grid. The purpose of the analysis was to identify how to renew and expand the transmission grid to decrease losses, increase the transmission capacity, facilitate for transmission line outages, and to make the transmission grid topology more robust. One of the driving forces behind the project is the transmission capacity limitations, which affect the reliability of supply negatively for the southern part of Sweden [2]. Another driving force is to enable connection of offshore wind farms that are planned to be built along the east-coast of Sweden [2].

The system analysis resulted in the biggest investment project in Svenska kraftnät's history, the NordSyd project. In the NordSyd project, major investments are planned in the north-south direction of the Swedish transmission grid. The geographical locations of the new transmission line terminals are twelve already existing substations, where six substations are in the southern part of Sweden, and six substations are in the northern part of Sweden [2].

2.4 Historical extreme weather events

Extreme weather events have caused severe damages to power systems worldwide [6]. Furthermore, HILP events have increased rapidly in frequency and magnitude during recent years [7]. In this section, the effects of historical extreme weather events studied in **Paper II** and **Paper III** are reviewed.

The Hurricane Sandy (October 29-30, 2012) inflicted damages measuring $70 billion US dollars and killed 233 people across eight countries from Canada to the Caribbean. When it reached the US coast, it was categorised as a Category 1-equivalent extratropical cyclone with wind gusts over 37 m/s, resulting in 300 000 people without electricity in Massachusetts only. Wind gust speeds during the Hurricane Sandy, measured at six different measurement sites along the southern coast of New England are shown in Figure 1.

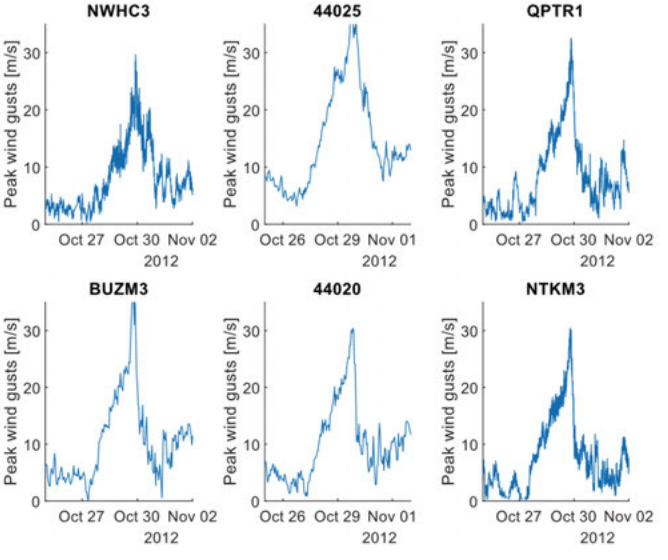


Figure 1. Wind gust speeds during the Hurricane Sandy at six different measurement sites. The figure is from **Paper II**.

The Winter Storm Nemo (February 8, 2013) caused hurricane-force wind gusts and heavy snowfall in New England. States of emergency was declared by state governors, and travel bans were put in place in multiple states in the USA. In total, about 700 000 people were affected by large power outages, mostly caused by wet snow.

The 2018 nor'easter (March 1-3, 2018) hit the coast of New England with hurricane-force wind gusts. The storm caused the death of 9 people, most due to falling branches and trees.

The 2021 nor'easter (October 27, 2021) was an erratic nor'easter and tropical cyclone that struck the east coast of the USA with strong winds, causing floodings in the affected areas. The storm caused the death of 2 persons and resulted in 617 000 people without electricity in the USA.

The Great Storm of 1987 (October 15-16, 1987) was an extratropical cyclone with hurricane-force winds striking against Great Britain and France, causing the death of at least 22 people. Wind gusts of 54 m/s were recorded, and the wind caused fallen trees which damaged railways, roads, and power lines.

Burn's Day Storm (January 25-26, 1990) was an extremely violent storm that hit north-western Europe with hurricane-force wind speeds. There were 47 people killed in the Great Britain, mostly caused by falling trees and collapsing buildings. Major power outages and severe floodings were caused by the storm.

The Floods of 2000 (October 2000) were a series of extreme flooding and storm events that hit several European countries. In Great Britain, thousands of homes were without electricity and the damages caused by the floodings were estimated to cost £1 billion GBP.

The Storms of 2013 (December 2013) were several storms that hit the Great Britain during December 2013. Extreme wind speeds resulted in falling trees which damaged cars, buildings, and power lines. Because of the storms, floodings were also affecting the country resulting in evacuation of thousands of households.

The Beast from the East (February to March 2018) was a weather phenomenon where polar air masses descended onto Great Britain, resulting in unusual low temperatures and lots of snow. Icy conditions and widespread snow caused several deaths in the Great Britain.

2.5 Vulnerability and resilience

The concept of vulnerability has been defined in multiple ways in previous research [1]. In [50], the vulnerability of the Nordic transmission grid was investigated aiming at identifying the situations, scenarios, and incidents leading to serious consequences for the power system. Vulnerability is defined in [51] as "an expression for the problems a system faces to maintain its function if a threat leads to an unwanted event and the problems the system faces to resume its activities after the event occurred”. Another definition used in the literature is “the weakness level of a system to failures, disasters or attacks” [52]. A definition of vulnerability, specifically focusing on vulnerability of power grids is “robustness or vulnerability (its opposite concept) are often used to measure to what extent a power grid has high or low reliability, respectively” [35]. Based on the aforementioned definitions, vulnerability is defined in **Paper I** as “the measure to which extent the nodes in a network are critical to the network’s structure and functionality”.

When it comes to the concept of resilience, a general definition is the ability to quickly recover or withstand a major disruption. In the context of power systems, resilience has been described as the ability to “anticipate extraordinary and high-impact, low probability events, rapidly recover from these disruptive events and absorbing lessons for adapting its operation and structure for preventing or mitigating the impact of similar events in the future” [53]. Further, an economic approach from a distribution system operator’s perspective was taken in [54], where the resilience of the distribution system was improved by minimizing the load shedding cost, hardening of wind turbines and power lines, and purchasing power from substations. The minimal load loss was used in [55] to optimize strategies to decrease the impact of wildfires on the New England 39-bus system using dynamic game methodology. In **Paper II** and **Paper III**, resilience is defined as the power system’s ability to handle loss of offshore wind power generation, without having to disconnect load from the grid to uphold the balance of the power system. In these two studies, loss of wind power generation is caused by offshore wind farms reaching their cut-out wind speed and thereby shutting down.

3 Methodology and data

In this chapter, the methodology and data used in **Paper I-III** are presented. In Section 3.1, the theory and analytical measures associated with complex networks are reviewed. In Section 3.2, the developed methods originating from AC power flow analysis are explained, and the algorithm and convergence strategies of the quasi-dynamic simulations are presented. Then, the power grid models used in the papers are presented in Section 3.3 and the wind farm specifications are presented in Section 3.4. The chapter concludes with a review of the data and data processing in Section 3.5.

3.1 Complex networks

Complex network concepts have been used extensively in research to study different kinds of real-world networks such as power systems, road infrastructure and the Internet [1,8,10–21,35,36,56–60]. The theory and concepts presented in the following subsections are based on **Paper I**.

3.1.1 Fundamental theory

In complex network theory, the fundamental concepts consist of a graph G containing a set of vertices V and a set of edges E weighted with a corresponding set of weights W, $G = \{V, E, W\}$ [21]. The vertices, edges, and weights can be identified by their indices i and j, for example e_{ij} for the edge between vertex v_i and v_j. Further, graphs are divided into directed and undirected graphs [35]. All graphs related to **Paper I** are undirected unweighted or undirected weighted graphs. From now on, the terminology ‘network’, ‘node’, and ‘link’ will be used consecutively when referring to the mathematical terminology ‘graph’, ‘vertex’, and ‘edge’.

3.1.2 Analytical measures

In its simplest form, the distance between any neighbouring nodes equals to one. However, the distance between nodes can be weighted using the weighting factors specified in the set of weights W. Thus, the distance d_{ij} between any nodes v_i and v_j in a power grid network can be calculated as

$$d_{ij} = \begin{cases} n_{ij}, & \textit{purely topological approach} \\ |X_{ij}|, & \textit{hybrid approach} \end{cases} \tag{3.1}$$

where n_{ij} is the number of steps along the shortest path between v_i and v_j, and $|X_{ij}|$ is the absolute value of the transmission lines' reactance between v_i and v_j, measured in ohm. Further, the reactance is defined as $X_{ij} = x_{ij}(U_{ij}) \cdot l$, where x_{ij} is the series reactance per length unit, U_{ij} is the transmission line voltage level and l is the physical length of the transmission line. The purely topological approach referred to in Equation 3.1 is associated with unweighted graphs, and the hybrid approach is associated with weighted graphs, as motivated in **Paper I**.

Centrality can be obtained as a function $C(v_i)$ where $C(v_i) > C(v_j)$ means that node v_i is more critical to the network than node v_j if and only if the condition is fulfilled [60]. Four centrality measures are used in **Paper I** to evaluate the criticality of the nodes in the Nordic transmission grid model: betweenness, degree, closeness, and combined centrality, which are presented below.

Betweenness centrality $C_B(v)$ quantifies how frequently a node v is found between two nodes s and t. It is calculated as

$$C_B(v) = \sum_{s \neq t \neq v \in V} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{3.2}$$

where σ_{st} is the total number of shortest paths between s and t, of which $\sigma_{st}(v)$ number of shortest paths pass through node v. The path length is calculated using Equation 3.1. Betweenness centrality quantifies the node interconnection and a high C_B score of node v means that a failure of node v results in a longer path between s and t. It can also lead to a complete node disconnection.

Degree centrality $C_D(v)$ quantifies how many links that are connected to node v and is calculated as

$$C_D(v) = \sum_{i=1}^{N} A_{vi} \tag{3.3}$$

where A_{vi} is the number of direct interconnections between node v and node i and $\{v, i, N\} \in V$. It can be interpreted as the influence node v has on its neighbouring nodes if it gets deactivated [10,35].

Closeness centrality $C_C(v)$ of a node quantifies how close a node v is all other nodes in the network. It is calculated as

$$C_C(v) = \frac{N-1}{\sum_i d_{vi}} \tag{3.4}$$

where d_{vi} is the distance from node v to node i and $\{v, i, N\} \in V$. The distances are calculated using Equation 3.1.

Combined centrality was introduced in **Paper I**. It is a straightforward, equally weighted centrality measure capturing the properties of the betweenness, degree, and closeness centrality measures. The measure origins from a heuristic approach and is calculated as

$$C_{comb}(v) = \frac{\frac{C_B(v)}{\sum_i C_B(i)} + \frac{C_C(v)}{\sum_i C_C(i)} + \frac{C_D(v)}{\sum_i C_D(i)}}{3} \tag{3.5}$$

where $C_{comb}(v)$ is the combined centrality for node v.

3.2 AC power flow

The theory and concepts presented in the following subsection is based on **Paper II** and **Paper III**.

3.2.1 Quasi-dynamic simulation algorithm

In **Paper II** and **Paper III**, quasi-dynamic simulations based on AC power flows are performed. The solver used is the fast decoupled method (FDXB) implemented as a package in MATPOWER [61]. The FDXB method is selected due to its reliability and short computational time [62]. Decreasing the computational time is valuable when performing power flow calculations iteratively for a substantial number of time steps.

The method developed in **Paper II** is further developed in **Paper III**, containing generator ramp rate bounds and a fifth convergence strategy. The method is described in Figure 2.

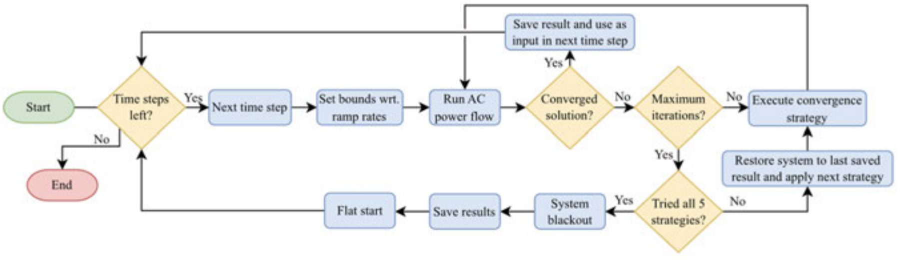


Figure 2. Flowchart illustrating the algorithm used to perform the quasi-dynamic simulations. The figure is from **Paper III**.

Even though the AC power flow method is a powerful tool when analysing power grids, it is widely known that it can lead to convergence issues where no solution could be found to the power flow equations [63]. However, load shedding is a strategy that can be used to find a converged solution [63]. In **Paper II** and **Paper III**, load shedding and power curtailment are used according to several predefined strategies. The strategies in **Paper II** are further refined in **Paper III** to increase the accuracy of the results, and a fifth strategy is also formulated in **Paper III**. The strategies in **Paper III** are as follows:

1. Reduce the largest load with 10%.
2. Reduce the largest generator with 5% (10% in **Paper II**).
3. Reduce the largest generator with 1% (10% in **Paper II**), load profile from last converged solution.
4. Reduce the largest load with 10%. Power generation profiles from last converged solution for all non-wind farms generators.
5. Shut down all wind power generation and reduce largest load with 10%.

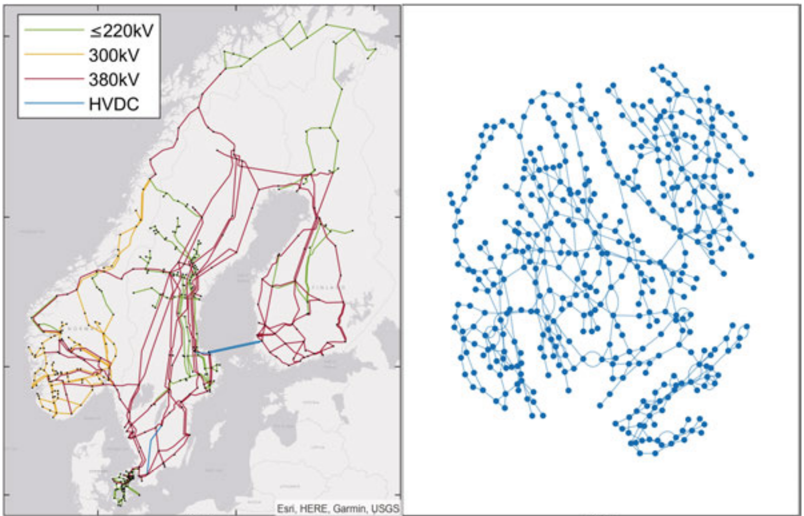
Each convergence strategy is applied iteratively up to 70 times. If no solution is found within 70 iterations for a specific strategy, the power system parameters are restored to the values of the last converged solution. Thereafter, the next strategy is applied. If no converged solution can be found with any of the named strategies, the results are interpreted as a total power grid blackout. In the case of a total blackout, all parameters are set to their initial values and a flat start is applied.

3.3 Power system models

This section presents the power system models used in **Paper I-III**.

3.3.1 Nordic model

In **Paper I**, a model representing the Nordic transmission grid is used as the test case. The model, which is called Nordic490, is a simplification of the transmission grids in Norway, Sweden, Finland, and eastern Denmark. It was first published in [64] with the aim to be an open-source power grid model fully based on open-source data. The model consists of 494 buses, 600 AC transmission lines of 132 kV up to 380 kV, and 65 transformers. In **Paper I**, the physical structure of the Nordic490 model is extracted and converted into a network representation with nodes and links. Based on assumptions of typical impedance values of transmission lines, together with the physical length of the transmission lines, weight factors are calculated for each link. The geographic and network representations of the Nordic490 model are shown in Figure 3.

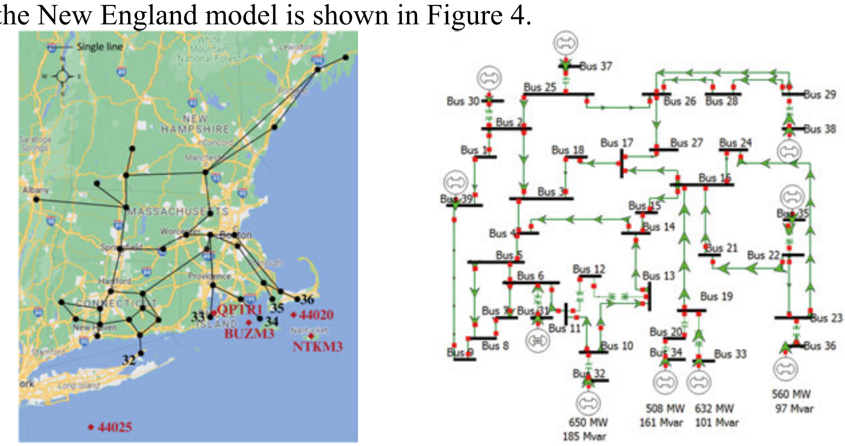


(a) (b)

Figure 3. Nordic490 model shown as (a) a geographic and (b) a network representation. The figure is from **Paper I**.

3.3.2 New England model

A model representing the New England power system, known as the IEEE39-bus New England system, is used in **Paper II** and **Paper III**. It is geographically located in the north-eastern USA, consisting of 39 buses with transmission lines and transformers. Between the interconnected buses there are single transmission lines. A geographic representation as well as a one-line diagram of the New England model is shown in Figure 4.



(a) (b)

Figure 4. (a) geographic and (b) one-line diagram representation of the New England model. The red squares in (a) mark the locations of the measurement sites capturing the wind data presented in Section 3.5.1. The figures are from **Paper III** and **Paper II**, respectively.

3.3.3 Great Britain model

A simplified version of Great Britain's power system is used in **Paper III**. It consists of 29 buses with transformers and transmission lines, and it has been retrieved from [65]. Compared with the New England model presented in Section 3.3.2, the Great Britain model has mostly double transmission lines between interconnected buses. Further, the grid is meshed to a higher degree than the New England model. A geographic representation of the Great Britain model is shown in Figure 5.

Figure 5. Geographic representation of the Great Britain power grid. The red squares mark the locations of the measurement sites capturing the wind data presented in Section 3.5.1. The figure is from **Paper III**.

3.4 Wind farm specifications

In this section, the wind farm specifications used in **Paper II** and **Paper III** are summarised.

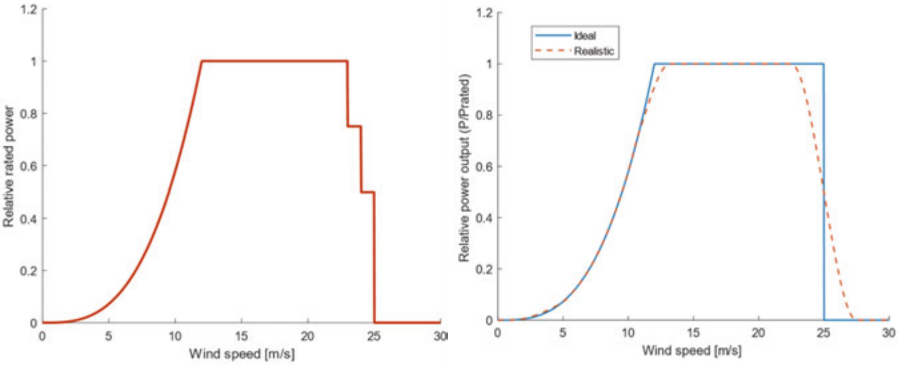
3.4.1 Technical data, power curves and power output

The wind turbines in **Paper II** and **Paper III** are assumed to have a blade radius $R_b = 65$ m, a rated wind speed $U_{rated} = 12$ m/s, and a cut-out wind speed $U_{cutout} = 25$ m/s. Thus, the relative power output from a single ideal wind turbine is calculated as

$$P = \begin{cases} 0, & U < U_{cutin} \\ \frac{1}{2}\rho C_p \pi R_b^2 U^3, & U_{cutin} \le U < U_{rated} \\ P_{rated}, & U_{rated} \le U < U_{cutout} \\ 0, & U \ge U_{cutout} \end{cases} \tag{3.6}$$

where ρ = 1.29 kg/m^3 is the air density, $C_p = 6.8 \cdot 10^{-8}$ is the aerodynamic performance constant, U is the wind speed, U_{cutin} is the cut-in wind speed, and P_{rated} is the rated power capacity.

To better describe the relationship between wind speed and power output for an entire offshore wind farm, the power curve is modified according to Figure 6 (a) in **Paper II** and the red dotted curve in Figure 6 (b) in **Paper III**.



(a) (b)

Figure 6. Relative power output as function of wind speed in (a) **Paper II** and (b) in **Paper III**.

The wind speeds recorded at the different measurement sites are used to calculate the power outputs based on the power curves shown in Figure 6 and the installed capacities of the wind farms.

3.4.2 Penetration levels

In **Paper II**, 6 penetration levels of installed offshore wind power capacity are investigated, called Case 1 in Table 1. In **Paper III**, 5 penetration levels and 3 different cases are investigated, see Table 1. Case 1 refers to the studies using the New England model and New England storms data, Case 2 refers to the study using the Great Britain model and Great Britain storms data, and Case 3 refers to the study using the Great Britain model and New England storms data.

Table 1. Penetration levels and corresponding integrated offshore wind farms. Case 1 is investigated in **Paper II** and Case 1-3 is investigated in **Paper III**. The table is inspired by **Paper III**.

Case	Penetration level	Penetration [%]	Wind farms integrated at bus	Case	Penetration level	Penetration [%]	Wind farms integrated at bus
Case 1	1	13	32	Case 2 & 3	1	5	1, 2
	2	21	32, 34		2	14	1, 2, 7, 10
	3	30	32, 34, 36		3	30	1, 2, 7, 10, 11, 12
	4	40	32, 33, 34, 36		4	37	1, 2, 7, 10, 11, 12, 20, 25
	5	50	32, 33, 34, 35, 36		5	49	1, 2, 7, 10, 11, 12, 20, 25, 26, 28
	6*	59	31, 32, 33, 34, 35, 36		-	-	-

*Penetration level 6 only included in **Paper II**.

3.5 Data

Geospatial wind data from historical extreme storm events are used in **Paper II** and **Paper III**. In this section, the data and data processing are presented.

3.5.1 Wind data

Historical wind gust data from four extreme storm events that hit New England are used in **Paper II** and **Paper III**: Hurricane Sandy (2012), Winter Storm Nemo (2013), 2018 nor'easter, and 2021 nor'easter. The data have been recorded at the measurement sites marked in Figure 4 (a) and are given with a time resolution of 6 minutes up to 1 hour.

In **Paper III**, geospatial wind gust data of five historical storms that hit Great Britain are used: The Great Storm of 1987, Burns' Day Storm (1990), The Floods of 2000, Storms of 2013, and The Beast from the East (2018). The wind data have been recorded at the measurement sites marked with red squares in Figure 5. The time resolution of the recorded wind data is 1 hour.

The specifications of the measurement sites and their corresponding offshore wind farms are presented in Table 2.

Table 2. Specifications of the measurement sites and their corresponding offshore wind farms in New England and Great Britain. The table is inspired by **Paper III**.

Bus number	Installed wind farm capacity [MW]	Measurement site		
		Name	Site elevation [m]	Altitude [m]
32	2 900	44025	0	4.1
33	2 608	QPTR1	1.6	7.0
34	2 032	BUZM3	0	24.8
35	2 748	44020	0	4.1
36	2 320	NTKM3	2.2	8.5
1 2	6 164 6 346	Peterhead Harbour	0	15.0
7 10	10 525 14 008	Boulmer	0	23.0
11 12	23 068 20 316	Blackpool	0	10.0
20 25	6 240 13 472	Wattisham	0	89.0
26 28	30 468 6 112	Langdon Bay	0	117.0

3.5.2 Data processing

Since the data were measured at different altitudes, a scaling formula is used to scale all wind data to a height of 100 meters above the water surface. The scaled wind speeds are calculated as $U_{100} = U_{ref}(100/z_{ref})^a$, where U_{ref} is the reference wind speed, z_{ref} is the altitude above ground, and a is the Hellman exponent. The value of the Hellman exponent a = 0.06 is selected based on the unstable wind conditions above the water surface [66].

In **Paper II**, linear interpolation of missing data points is applied. However, to create a more realistic interpolation, a stochastic approach based on uniform white noise is adopted in **Paper III**. The procedure of the stochastic interpolation is as follows:

1. The data are interpolated using a piecewise cubic interpolating polynomial function.
2. A random number $n_{rand} = \{-2 \leq n_{rand} \leq 2 \; ; n_{rand} \in \mathbb{R}\}$ generated from a uniform distribution is drawn for each interpolated 6 minutes time step.

3. The random numbers are added to each interpolated value creating a slightly oscillating, realistic time series of 6 minutes resolution wind data.

An example of the actual measurements and the interpolation with and without randomized values added is shown in Figure 7.

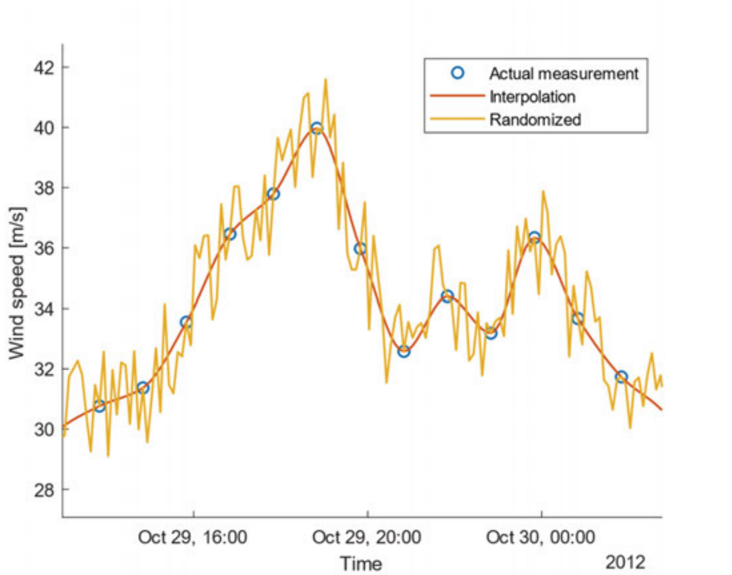


Figure 7. Actual measurements, interpolation using piecewise cubic polynomial, and the output function including the randomized values. The example is taken from Hurricane Sandy, measured at site 44025. The figure is from **Paper III**.

4 Results

In this chapter, the results presented in **Paper I-III** are given. In Section 4.1, the results regarding node criticality are presented. In Section 4.2, the results concerning resilience to storm conditions of power systems with large offshore wind farm dependencies are given.

4.1 Node criticality

In this section, the main results from **Paper I** are presented. The results address the network analysis made of the Nordic transmission grid model, starting with betweenness, degree, and closeness centrality. The section ends with a presentation of the results of the combined centrality measure and how the results relate to the system analysis presented by Svenska kraftnät.

4.1.1 Betweenness centrality

The geographic and network representations of the Nordic grid model, with respect to the weighted betweenness centrality, are shown in Figure 8. The areas where the high scored nodes are located are highlighted with red circles.

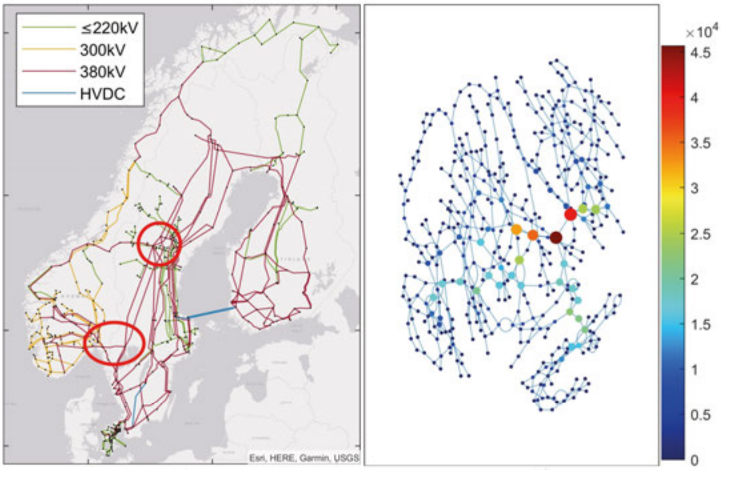


Figure 8. Weighted geographic and network representations of the betweenness centrality scores. The figure is from **Paper I**.

With respect to the betweenness centrality, the most critical nodes are placed in two areas: in the middle part of Sweden and in the south-eastern part of Norway bordering Sweden. From the network representation, it can be seen that most of the nodes have a centrality score in the bottom of the score range. However, there are nodes that stand out significantly in terms of criticality, placed in the centre of the network.

4.1.2 Degree centrality

Figure 9 shows the geographic and network representations of the Nordic transmission grid model with respect to the degree centrality scores. The values are normalized by the factor *(N-1)*$^{-1}$, which is not explicitly stated in **Paper I**. The high scored areas are located and highlighted with red circles.

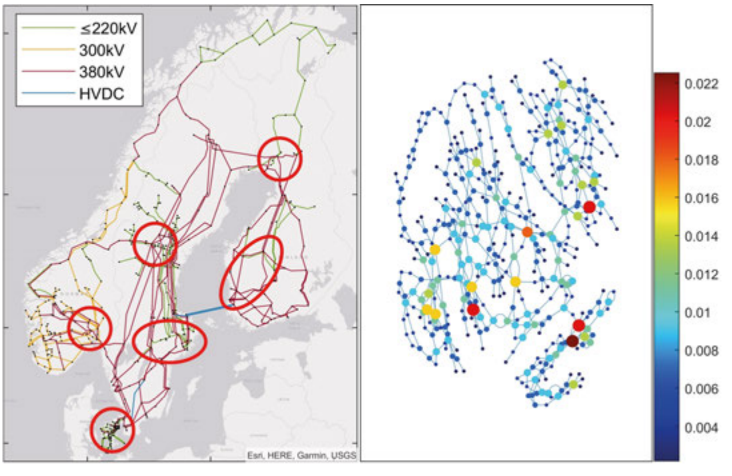


Figure 9. Geographic and network representations of the size of the normalised degree centrality scores. The figure is from **Paper I**.

The high scored nodes with respect to degree centrality is more spread out than in the case of betweenness centrality. Geographically, the high scored nodes are located all around the Nordic countries.

4.1.3 Closeness centrality

The weighted closeness centrality scores of the Nordic transmission grid model are illustrated in Figure 10. The high scored areas are highlighted with red circles in the geographic illustration.

With respect to the closeness centrality, the most critical nodes are located in the southern and middle part of Sweden. However, compared to the betweenness and degree centrality scores, the closeness centrality scores are more evenly distributed in the network. This can be observed in the network representation in Figure 10.

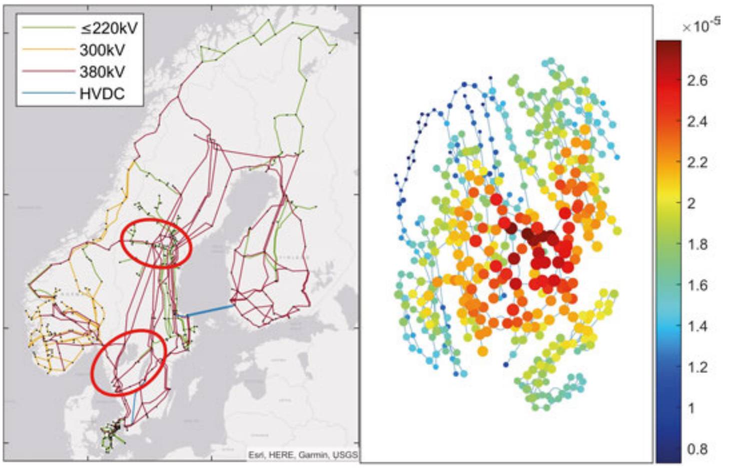


Figure 10. Weighted geographic and network representations of the closeness centrality scores. The figure is from **Paper I**.

4.1.4 Combined centrality

From Figure 11, the weighted combined centrality scores of the Nordic transmission grid model can be obtained. The red circles in the geographic representation mark the high scored areas.

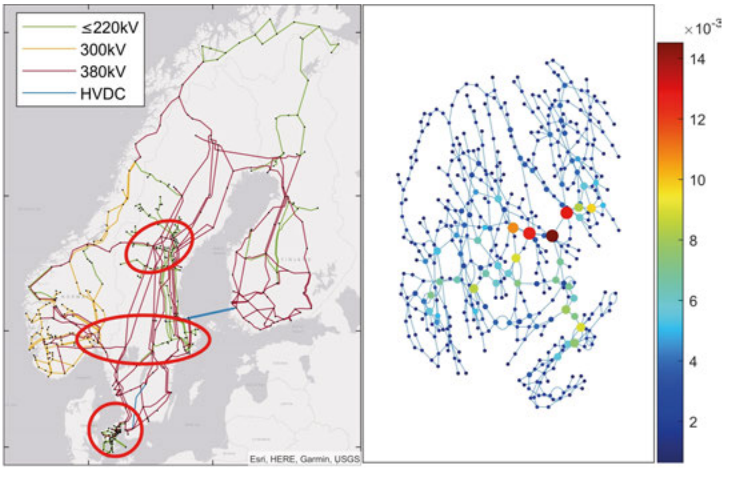


Figure 11. Weighted geographic and network representations of the combined centrality scores. The figure is from **Paper I**.

Considering the network representation in Figure 11, the nodes standing out in terms of criticality are mainly placed in the centre of the network. The geographic interpretation shows that the highest scored areas are in the middle part of Sweden, in the area between Oslo in Norway and Stockholm in Sweden, as well as in the eastern part of Denmark.

4.1.5 Comparison with Svenska kraftnät's system analysis

This section evaluates the results of **Paper I** through a qualitative comparison with a system analysis performed by Svenska kraftnät. The text is mainly from **Paper I**.

The main purposes of the NordSyd project, as presented by Svenska kraftnät, are to decrease losses, facilitate for transmission line outages, increase transmission capacity, and to make the grid topology more robust [2]. One of the driving forces behind the project is the transmission capacity limitations which have a negative impact on the reliability of supply for southern Sweden [2]. Thus, one of the NordSyd project's outcome is a more robust transmission grid which leads to a reduced vulnerability. From the system analysis performed by Svenska kraftnät, 6 substations in the middle of Sweden and 6 substations in the southern of Sweden were identified as objects in the transmission grid where major investments will be done, hereafter called NordSyd substations. Thus, it is reasonable to assume that these substations pose critical nodes in the transmission grid where the transmission capacity must be increased. Even though the criticality of specific substations in a grid is not openly available, it is argued that the criticality of the substations can be conjectured based on the abovementioned reasoning.

All four centrality measures were able to identify some of the NordSyd substations, but the weighted and combined centrality measure was the best measure in finding these substations. A total of five out of twelve NordSyd substations were identified with the proposed model. The model successfully identified nodes geographically located in the regions where all the NordSyd substations are placed. However, it should be emphasised that even though the model is able to find some nodes indicating to be critical, it does not imply that all critical nodes have been found. The results from this method should therefore not be considered conclusive.

By comparing the results from the present study and the system analysis performed by Svenska kraftnät, it can be concluded that the correlation between the results is substantial. However, the results might not be enough to be considered as a proof since they are more indirectly related to what is presented by Svenska kraftnät. Yet, the results strengthen the hypothesis that a complex network approach is relevant when identifying the critical nodes in a real transmission grid. This applies even though simplifications have been made and that the model is based solely on open-source data. This implies that a complex network approach based on open-source data can generate relevant and grounded results when searching for critical nodes in real transmission grids.

4.2 Resilience to storm conditions

In this section, the most important results from **Paper II** and **Paper III** are presented. These two papers investigate the resilience to storm conditions of power systems with varying dependencies on offshore wind. The resilience is measured in terms of disconnected load caused by offshore wind farms shutting down due to cut-out wind speeds. Two power systems are presented in this section, New England, and Great Britain power system.

4.2.1 New England case

In **Paper II**, a method for quantifying the resilience of a power system subject to extreme storm events is presented. The results from that method, focusing on the New England power system subject to the Hurricane Sandy (2012) is shown in Figure 12. The figure shows the parameters of interest during the storm peak for penetration level 1, 3, 4, and 5 corresponding to percental penetrations of 13%, 30%, 40%, and 50%, respectively. For results concerning other penetration levels, see **Paper II**.

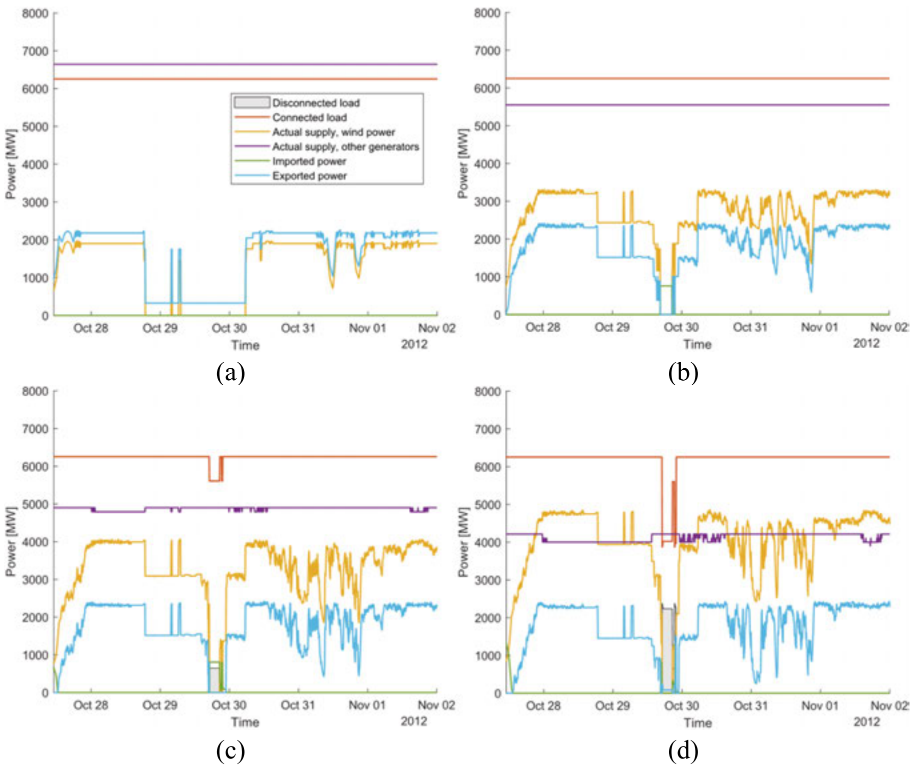


Figure 12. Time series of the storm peak of Hurricane Sandy (2012), applied to the New England power system. Subfigures (a)-(d) represent the offshore penetration levels 1, 3, 4, and 5, respectively. The subfigures are from **Paper II**.

As can be seen from Figure 12 (a), the power generation from the offshore wind farms drops down to 0 MW when the storm approaches its peak. The drop in power generation is due to wind speeds exceeding the cut-out velocity, resulting in wind turbines shutting down. As can be seen from Figure 12 (a)-(b), the load connected to the grid stays at a constant value of 6.3 GW and is thereby unaffected by the lack of wind power generation during the storm peak. The generation capacity of the other generators in the power system, power import, as well as a sufficient strong grid are capable of compensating for the loss of wind power production. However, for penetration level 4, 650 MW of load must be disconnected during the storm peak to avoid a voltage collapse. The need for load disconnection rises significantly for penetration level 5 where 2.2 GW of load gets disconnected during the storm peak.

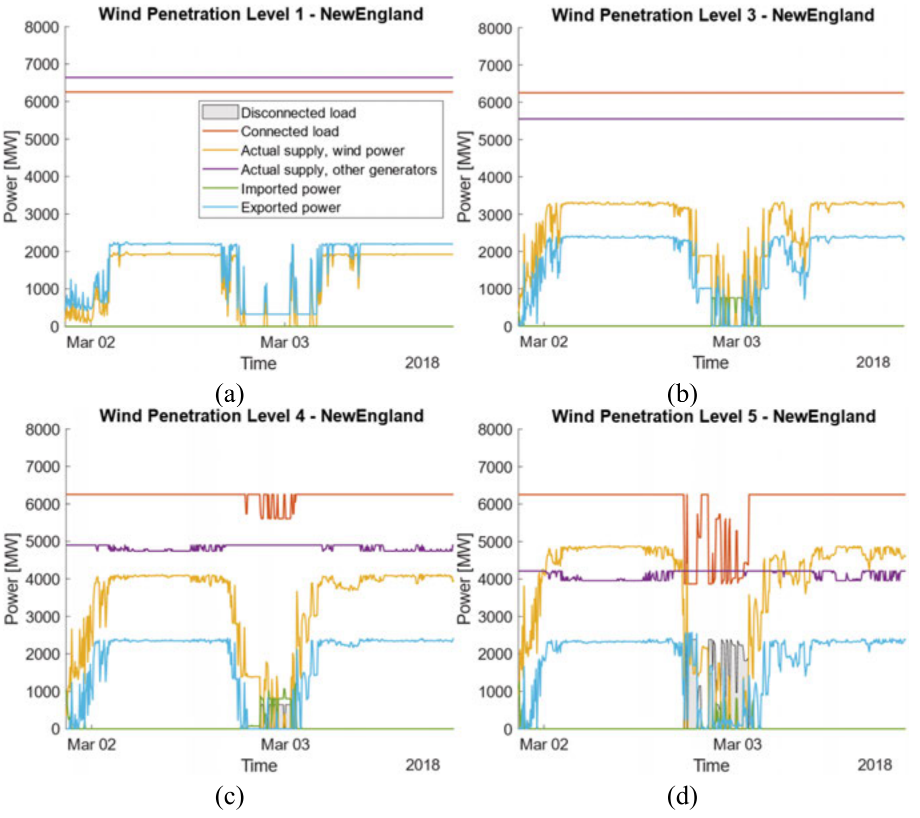


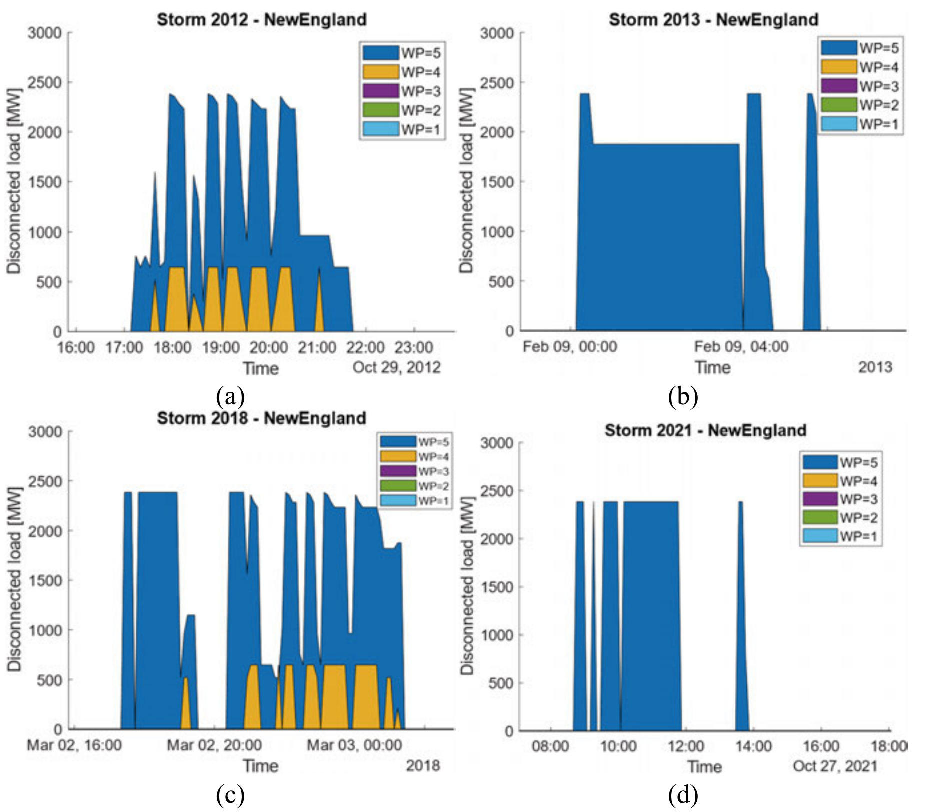
Figure 13. Time series of the storm peak of 2018 nor'easter, applied to the New England power system. Subfigures (a)-(d) represent the offshore penetration levels 1, 3, 4, and 5, respectively. The subfigures are from **Paper III**.

In **Paper III**, the method presented in **Paper II** is further improved and the data processing is refined. The results from the improved method, focusing on the New England power system subject to the 2018 nor'easter is shown in Figure 13. The figure shows the parameters of interest during the storm peak for penetration level 1, 3, 4, and 5 corresponding to percental penetrations of 13%, 30%, 40%, and 50%, respectively. For results concerning other penetration levels, see **Paper III**.

As can be obtained from Figure 13, during the end of March 2, all offshore wind farms get completely shut down due to wind speeds exceeding the cut-out velocity. The fluctuations of wind power production during the storm peak are due to wind speed data oscillating close to the cut-out wind speed. Similar to the results presented in Figure 12, there is no need for load disconnection during the storm peak for penetration level 1 or 3. Instead, the need for load disconnection appears for penetration level 4 where 650 MW of load gets disconnected, and increases significantly for penetration level 5 where 2.4 GW of load gets disconnected.

Even though the method is refined in **Paper III**, the general characteristics of the results are the same as in **Paper II**.

From Figure 14, the disconnected load for all 4 storms, and all 5 offshore wind penetration levels presented in **Paper III** can be obtained. No load gets disconnected in any of the 4 storms for wind penetration level 1-3.



(a) (b) (c) (d)

Figure 14. Disconnected load during (a) Hurricane Sandy, (b) Winter Storm Nemo, (c) 2018 nor'easter, and (d) 2021 nor'easter. The subfigures are from **Paper III**.

A maximum amount of 650 MW of load, corresponding to 10% of the total load demand, gets disconnected during Hurricane Sandy and 2018 nor’easter for penetration level 4. These power outages last for in total 1.5 hours during Hurricane Sandy and for 2 hours during 2018 nor’easter, which is shown in Figure 14 (a) and (c). No load gets disconnected during Winter Storm Nemo or 2021 nor’easter for wind penetration level 4. Considering wind penetration level 5, a significant increase in terms of disconnected load can be seen for all 4 storms. At most, 2.4 GW of load, corresponding to 33% of the total load demand, gets disconnected during all 4 storm peaks. The most severe power outage is caused by the Winter Storm Nemo, causing a maximum power outage of 1.9-2.4 GW for as long as 4.5 hours.

4.2.2 Great Britain case

The parameters of interest of the Great Britain power system model, subject to the Burns’ Day Storm (1990) are shown in Figure 15.

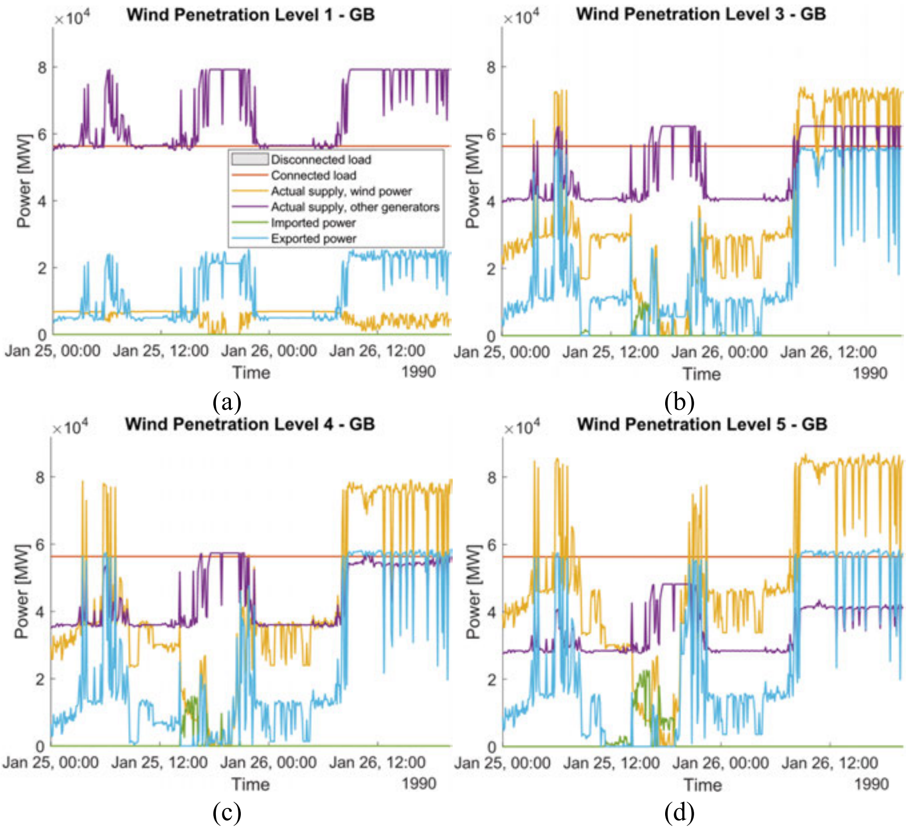


Figure 15. Time series of the storm peak of Burns’ Day Storm (1990). (a) to (d) represent the 4 offshore wind penetration levels of 5%, 30%, 37%, and 49%, respectively. The subfigures are from **Paper III**.

From Figure 15, it can be seen that no load has to be disconnected for any of the investigated penetration levels. This contrasts with the cases of the New England model presented in Section 4.2.1, where load must be disconnected to avoid a voltage collapse. Instead, the power production capacity of the other generators in the grid, together with a significantly higher transmission capacity are enough to compensate for the loss of offshore wind power production. Moreover, the results show that the other generators in the grid have a ramp rate high enough to successfully balance the fluctuations in power production from the offshore wind farms.

A fictitious scenario with the 2018 nor'easter storm that hit New England, applied to the British test system, is presented in **Paper III** and the results are shown in Figure 16.

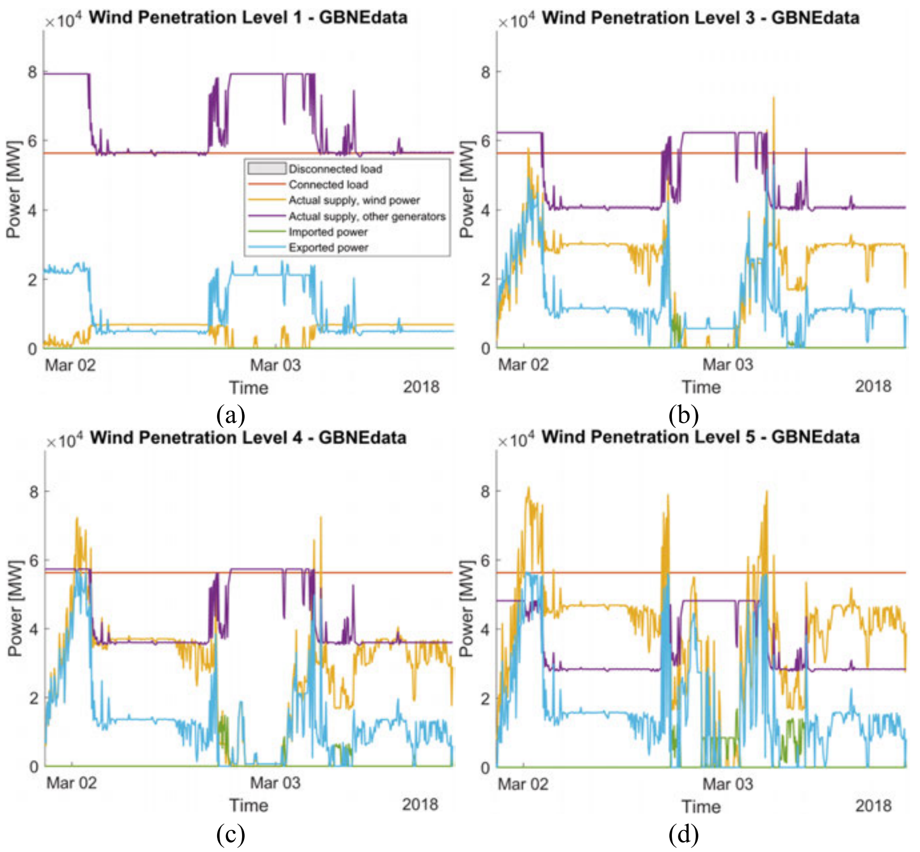


Figure 16. Time series of the storm peak of the 2018 nor'easter storm, applied to the British power system. (a) to (d) represent the 4 offshore wind penetration levels of 5%, 30%, 37%, and 49%, respectively. The subfigures are from **Paper III**.

In contrast with the results presented in Section 4.2.1, when the 2018 nor'easter storm was applied to the New England power system, the British power system stays intact in terms of connected load for all investigated wind power penetration levels. No load must be disconnected during the 2018 nor'easter storm to avoid a voltage collapse. Instead, the power transmission capacity and the ramp rates of the other power generation facilities are enough for the Great Britain power system model to avoid load disconnection.

4.2.3 Factors affecting the power system's resilience

From the results of the New England cases presented in **Paper II** and **Paper III**, it can be concluded that there is a non-linear relationship between the number of offshore wind farms integrated into the power system and the disconnected load. There is a penetration level threshold where the offshore wind farms go from not affecting the power system resilience to where they start to affect it. When the offshore wind farms start to affect the resilience of the power system, the increase in terms of disconnected load is significant. However, the penetration level threshold differs from grid to grid, as can be concluded when comparing the results from the New England and Great Britain cases. Thus, the general conclusion is that thresholds exist and should be considered when integrating high penetrations of offshore wind.

When comparing the results of the New England and Great Britain cases presented in **Paper III**, it can be concluded that the results differ significantly in terms of disconnected load. The differences are explained by five main reasons:

1. The Great Britain model is meshed to a higher degree than the New England model. The more a grid is meshed, the less is the risk for bottlenecks in the grid. Moreover, the robustness is increased with a higher degree of meshing.
2. The transmission capacity of the Great Britain model is higher than that of the New England model. This is due to the double transmission lines between most of the interconnected buses. Thus, power can be transmitted from high to low production areas more effectively.
3. There are more generators in the Great Britain model than in the New England model, which contributes to uphold the local power balance without having to transmit all electric power from distant parts of the grid.
4. Considering the relationship between installed generation capacity and active load demand, the Great Britain model has 46% higher installed capacity than active load demand. The New England model has 18% higher installed generation capacity than active load demand. This indicates that the higher the installed capacity of conventional generators, the better when integrating offshore wind power.
5. The wind farms are distributed over a larger geographic region in the Great Britain model than in the New England model. The

substantial geographical spreading of the offshore wind farms decreases the correlation of their power output, which increases the resilience of the power system.

The more a power system is adapted to these five dimensions, the higher the resilience to storm conditions will be when integrating large amounts of offshore wind.

5 Discussion and future work

In this chapter, the results from **Paper I-III** are further discussed in Section 5.1, and in Section 5.2 proposals for future research are summarised.

5.1 Discussion

In the field of network analysis, complex network methods have reached a significant scientific impact. However, the practical applicability of complex network concepts in the context of power grid research is still open to debate. The results from **Paper I** indicate that the proposed method, based on complex network concepts, pose a useful and yet not computationally heavy method for analysing the structural vulnerability of a model representing a real transmission grid. Thus, the relevance of complex network methods, in the context of power grid analysis, is strengthened.

Since the society is becoming more and more electrified, and since the number of HILP events is supposed to increase, there is a need for further development of power grid analysis tools. One of these tools could be the complex network approach, which makes the method and results presented in **Paper I** relevant. Since different analysis methods capture different perspectives, a complex network approach could be considered as a complement to other methods such as power flow analyses.

A challenge when using models of real transmission grids, such as in **Paper I**, is that it is difficult to fully validate the results. Such validation would require access to data, some of which are often confidential. However, what has been shown in **Paper I** is that results and their methods can be strengthened though qualitative comparisons with publicly available information.

In the next decades, large dependencies on power production from offshore wind are expected. Since extreme weathers are expected to increase in frequency and intensity, research on power system resilience to such extreme events is of importance. In **Paper II**, the proposed method is used to quantify the resilience to storm conditions of a power system with varying dependencies on offshore wind. This method was further developed and used in **Paper III**, where a comparison of two different power systems with significantly different technical properties is presented. Thus, the method proposed, and the generated results are relevant.

The results presented in **Paper II** and **Paper III** show that the resilience of a power system with large dependence on offshore wind is highly dependent on the physical structure of the grid as well as the power grid control. Thus, proper power grid adaptions and well formulated control strategies are necessary to successfully integrate large amounts of offshore wind. However, adjusting and expanding a real power grid is both expensive and time-consuming. Thereby, power grid adaptions in real-life are to be considered as a long-term goal while implementing well formulated grid control strategies can be done immediately.

5.2 Future work

In **Paper I**, the criticality of the nodes is solely based on the interconnections between the nodes. Even though the links between the nodes are weighted, the nodes themselves are unweighted. Thereby, formulating a methodology that can be used to weight the nodes themselves can be of interest. Examples of node weighting factors are if the node is connected to a generator, if the generator connected to the node is variable or controllable, and the size of the load connected to the node. Further, appliance of complex network methods on real transmission and distribution grids must be done.

In **Paper II** and **Paper III**, resilience is measured in terms of the power systems' ability to handle loss of offshore wind power generation without having to disconnect load. The offshore wind farms are shut down due to wind speeds exceeding the cut-out velocity. In future studies, more circumstances associated with extreme storm events could be included in the resilience analysis. Two examples of such factors are the risk of getting a wind turbine generator failure or wind turbine foundation breakdown. Furthermore, the methodology proposed in **Paper III** can be further developed, including more sophisticated curtailment and load disconnection strategies.

6 Conclusions

The overall purpose of the thesis has been to develop, test, and evaluate methods to quantify the vulnerability and resilience of power grids to HILP events. The conclusions to the respective aims are presented below.

Aim I

Develop, test, and evaluate methods, based on complex network theory, to quantify the structural vulnerability of a model representing a real power grid.

- A new measure originating from complex network theory, the weighted combined centrality measure, was developed in **Paper I**.
- The method was tested on a model representing the Nordic transmission grid to quantify the structural vulnerability of the grid.
- The results were evaluated based on a qualitative comparison with a system analysis published by the Swedish TSO Svenska kraftnät. From the comparison, the relevance of the method has been strengthened.
- The results indicate that complex network concepts appear to pose a useful and yet not computationally heavy method for structural vulnerability analyses of real transmission grids.
- The proposed method's advantages are twofold. Firstly, the method is computationally inexpensive, enabling for fast analyses of large power grids with reasonable processor capacity. Secondly, the method is suitable to use without detailed information of the power system parameters.

Aim II

Quantify the resilience of a power system with large dependency on offshore wind, subject to extreme weather events, by using a power flow based method.

- A method based on quasi-dynamic AC power flow analysis was developed in **Paper II** to quantify the resilience of a power system with large dependencies on offshore wind.

- Wind data from 4 historical extreme weather events; Hurricane Sandy (2012), Winter Storm Nemo (2013), the 2018 nor'easter, and the 2021 nor'easter were used to generate power production profiles for 1 to 6 offshore wind farms, corresponding to 13-59% offshore wind penetration, located along the southern New England coast.
- The results show that the power grid has a good resilience to storm conditions with a maximum wind power penetration level of 30%. With a wind power penetration level of 40% or higher, load has to be disconnected from the grid during the storm peak due to the lack of power production. The relationship between installed wind power capacity and disconnected load is non-linear.
- The results highlight the importance of well-suited grid adaptions and thorough grid analyses to create a resilient power system with high dependence on offshore wind.

Aim III

By comparing two power system models with large dependencies on offshore wind, identify and evaluate parameters affecting the resilience of power systems subject to extreme weather events.

- By investigating two power systems' resilience to historical storm conditions in **Paper III**, the New England and the Great Britain power grid, parameters affecting the resilience of power systems with large dependencies on offshore wind were identified.
- The comparison of the results of the two grid models highlights 5 physical parameters affecting the resilience of a power grid: degree of meshing, transmission capacity, number and distribution of generators, degree of generation overcapacity, and geographical distribution of the offshore wind farms.
- The New England model has a good resilience to storm conditions with an offshore wind penetration level of 30% whereas the corresponding number of the Great Britain model is at least 49%.
- The importance of sophisticated power grid control to successfully integrate large amounts of offshore wind is emphasised.

7 Summary of papers and my contributions

Paper I

Power grid vulnerability analysis using complex network theory: A topological study of the Nordic transmission grid

In this paper, a method originating from complex network theory is implemented and used to quantify the structural vulnerability of an open-source transmission grid model representing the Nordic transmission grid. Five analytical measures are used to quantify the criticality of the nodes in the grid: clustering coefficient, and betweenness, closeness, degree, and combined centrality. The centrality measures are weighted with respect to the estimated series reactance of the transmission lines. The results are presented in network and geographic representations and are compared qualitatively with an open-source system analysis performed by the Swedish transmission system operator Svenska kraftnät. In conclusion, the weighted and combined centrality measure performed the best in terms of identifying critical nodes in the Nordic transmission grid.

The author of this thesis collected the data, developed the method, performed the calculations, did most of the analysis, and wrote the paper.

The paper is peer-reviewed and published in the journal *Physica A* 626:129072 (2023).

Paper II

Resilience to storm conditions of power systems with large dependencies on offshore wind

In this paper, a method based on quasi-dynamic AC power flows is formulated to investigate the resilience of a power system subject to hurricane events. The power grid model used is the IEEE39-bus New England system, with varying penetration of offshore wind. The results show that an offshore wind penetration level of 30% or less results in a power system resilient to hurricane events, with no need for load disconnection. However, when increased to 40% offshore wind penetration, 10% of the total load demand gets disconnected during the storm peak. With a penetration of 50% offshore wind, the disconnected load ranges from 1/3 of the total load demand, to a total power system blackout.

The author of this thesis developed the method further, performed the calculations, did most of the analysis, and wrote most of the paper except the abstract and introduction.

The paper is a peer-reviewed conference paper from the EERA DeepWind Conference, January 18-20, 2023, Trondheim, Norway. The paper is accepted and is to be published in *Journal of Physics: Conference Series* during autumn 2023.

Paper III

Resilience to extreme storm conditions: A comparative study of two power systems with varying dependencies on offshore wind

In this paper, a comparison between the New England and the Great Britain power grid models' resilience to historical extreme storm conditions is conducted. The method formulated in **Paper II** is further developed and the data processing is significantly refined. The offshore wind penetrations are set to vary between 5% and 50%, and the results show significant differences between the two power system models. While load must be disconnected for the New England model during the storm peaks, the Great Britain model stays intact in terms of connected load with an offshore wind penetration of at least 49%. In the New England case, load must be disconnected when integrating 40% or more offshore wind.

The author of this thesis developed the method further, performed the calculations, did the analysis, and wrote the paper except the introduction.

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8 Svensk sammanfattning

Elsystem världen över genomgår just nu en betydande förändring. Den pågående elektrifieringen av samhället leder till ett markant ökat elbehov, något som ställer högre krav på såväl elnätet som elproduktionskällorna. Utöver detta håller en allt större del av elproduktionen på att övergå från användning av fossila bränslen till att baseras på intermittent förnybar elproduktion. Denna omvandling av elsystemet skapar både möjligheter och leder till utmaningar.

Intermittenta förnybara energikällor såsom vind- och solkraft har bland annat egenskapen att dess produktion varierar över tid och att denna variation inte går att styra i någon större utsträckning. Detta skapar utmaningar i elsystemet eftersom det ibland produceras mer el än vad som konsumeras och vice versa. Eftersom el behöver konsumeras och produceras samtidigt och i samma kvantitet för att balansen i elsystemet ska upprätthållas kan det uppstå en obalans om det produceras för mycket eller för lite el. Det faktum att produktionen hos intermittenta förnybara energikällor inte går att styra gör att dem därmed riskerar att försämra stabiliteten i elsystemet. Denna minskade stabilitet kan i sin tur göra elsystemet mer sårbart för störningar orsakade av yttre påverkan, inte minst sådana händelser som sällan inträffar men vars konsekvenser blir omfattande. Sådana händelser kan till exempel utgöras av extremväder av olika slag såsom stormar, översvämningar eller omfattande skogsbränder.

De senaste åren har en ökning av extremväder setts runt om i världen. I takt med den globala uppvärmningen förväntas dessa händelser öka alltmer, både i antal och intensitet. Detta är något som i hög grad påverkar elsystemet som dagligen utsätts för externa påfrestningar, påfrestningar som alltså förväntas öka i framtiden.

En av de intermittenta förnybara energikällorna som fått mest utbredning hittills är landbaserad vindkraft. Dock har motståndet mot denna typ av vindkraft ökat i delar av världen bland annat med argumentet att den gör för stort visuellt ingrepp i naturen. Detta gör att havsbaserad vindkraft kommit att bli en lovande teknik. Havsbaserad vindkraft har bland annat fördelarna att den placeras i områden där människan sällan störs av dess närvaro och dessutom är vindförhållandena till havs mer fördelaktiga än på land. Därmed har planerad utbyggnad av havsbaserad vindkraft ökat kraftigt senaste åren.

Sammanfattningsvis sker alltså en omfattande elektrifiering samtidigt som andelen intermittent förnybar elproduktion ökar i elsystemet. Utöver detta förväntas även de externa påfrestningarna från extremväder tillta ytterligare.

Detta gör det viktigt att hitta metoder för att kvantifiera sårbarheter i elnät. Vidare är det viktigt att undersöka hur motståndskraften mot extremväder påverkas av en hög andel havsbaserad vindkraft integrerad i elsystemet. Detta är forskningsområden som denna avhandling har för avsikt att adressera.

Sårbarhet utifrån ett topologiskt perspektiv har undersökts med hjälp av koncept hämtade från komplex nätverksteori. Genom att studera en modell av det nordiska stamnätet kunde verklighetsförankrade resultat genereras, vilka sedan kunde jämföras kvalitativt med öppen information publicerad av den svenska stamnätsoperatören Svenska kraftnät. Jämförelsen visade en god överensstämmelse mellan kritiska noder i nätmodellen och stamnätsstationer som utifrån informationen från Svenska kraftnät kan antas vara viktiga i det nordiska stamnätet. På så sätt har det styrkts att koncept från komplex nätverksteori kan användas för att studera sårbarheter i elnät.

Motståndskraft utifrån perspektivet av att kunna stå emot följdeffekter av stormar som slår mot elnät har undersökts med hjälp av metoder baserade på lastflödesberäkningar. Utmaningarna för elnät utsatta för stormar är många, men en av dessa är att vindkraftverk riskerar att stänga av sin elproduktion om det blåser för mycket. Detta för att skydda vindkraftverken mot för kraftiga vibrationer. I händelse av en storm som slår mot ett elnät så kan avstängda vindkraftverk orsaka effektbrist vilket kan tvinga nätoperatören att koppla från last. I värsta fall kan en snabbt minskad elproduktion leda till spänningskollaps och därmed ett elnät som släcks ner. Faktorer som påverkar hur känsligt ett elnät med hög andel havsbaserad vindkraft är för stormar har identifierats. Genom fallstudier har det hittats nätspecifika gränsvärden för hur mycket havsbaserad vindkraft som kan integreras i elsystem innan problematiken med effektbrist under stormar inträffar.

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