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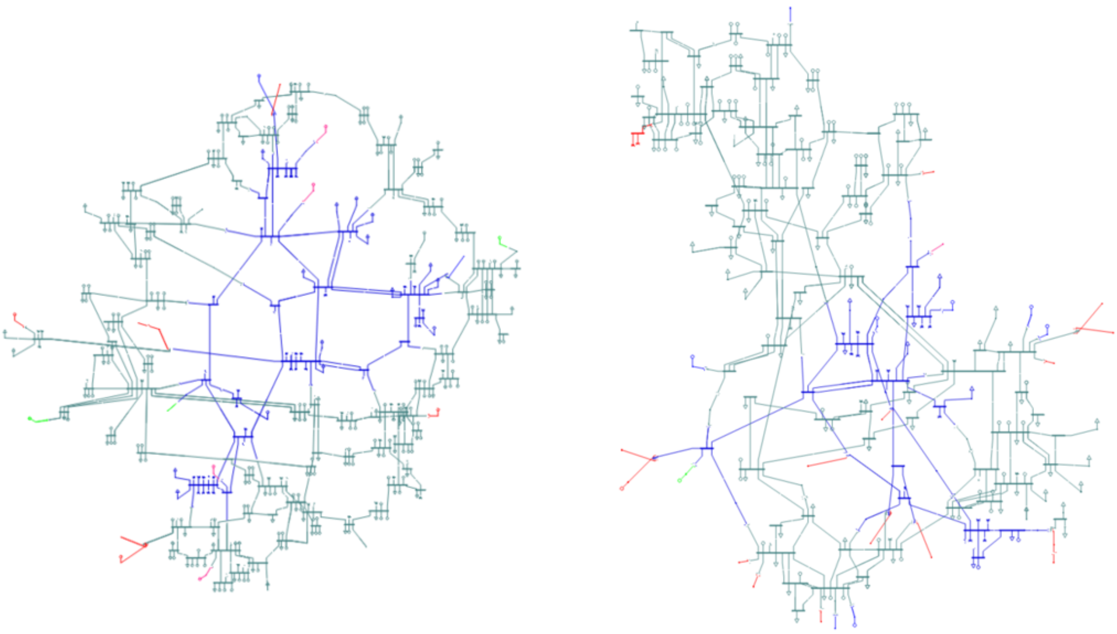

ENTSO-E grid data and generation modulation

Power flow and grid analysis of Denmark with equivalent reduced network in PSS/E

Master's thesis in Electric Power Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Slider diagram from PSS/E of the Danish transmission system

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Abstract

Many software and models display electric transmission systems without any constraints, i.e. it uses a *copper plate model*, which disregards both loop-flows and congestion. The power market dispatch model BID3 views each country as a copper plate, but with limited cross-border transmission capacity. This thesis introduces grid constraints by an equivalent reduced network in PSS/E of the Danish electric transmission system based of data from European Network of Transmission System Operators for Electricity (ENTSO-E) which could then be used to improve the accuracy of BID3. The ENTSO-E data is converted from CIM- to RAW-format used by PSS/E, and the BID3 results were included as input data for four simulation cases. These RAW-files were simplified with a PSS/E function called EEQV, which constructs equivalent networks. Two methods, A and B, were used which only retains boundary buses and buses connected to either phase shifting transformers or generators. The difference being that Method B also moves generators to a neighboring bus with a higher voltage level. Method A managed to reduce the number of buses from 284 to 164 while method B got down to 147. This thesis deems the EEQV-function to be sufficient in creating simplified grid models and both methods produce adequate representations of the grid. Method A retains more units in the grid, i.e. it is more complex, while Method B creates a more reduced network, although with marginal lower losses than the original case.

Keywords: ENTSO-E, PSS/E, European grid, Equivalent reduced network, Transmission system, EU, Denmark, CIM, BID3, EEQV

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Josef Johansson and Patrik Pettersson
Gothenburg, May 2021

Acronyms

ACER the European Union Agency for the Cooperation of Energy Regulators. 3

CIM Common Information Model. 14–16, 19

DSO Distribution system operator. 13, 43, 48

EMI electromagnetic interference. 12, 48

ENTSO-E European Network of Transmission System Operators for Electricity. v, 1, 3, 4, 13, 14, 19–21, 25–27, 34, 35, 41, 43, 46, 47

HLHP High load and high production. 23, 38, 43, 46

HLLP High load and low production. 23, 38, 46

HVDC high voltage direct current. 10, 12

LLHP Low load and high production. 23, 46

LLLP Low load and low production. 23, 38, 41, 43, 46

mRID Master Resource Identifier. 15, 16

PST phase shifting transformer. 11, 30–32, 39, 48

PV photovoltaic. 9, 24, 27, 48

RES Renewable Energy Sources. 6, 7, 10, 21, 48

SA synchronous areas. 3, 4, 9, 28

TSO Transmission system operator. 3, 5, 9, 10, 13, 14, 20, 25, 26, 43, 48

WP Wind power. 9, 24, 25, 27, 44, 48

Contents

1
Introduction

1.1 Background

The European electric grid is a multilateral cooperation that interconnects the different national electric transmission systems. This piece of infrastructure creates an international market for energy, where actors from different nations can purchase electrical energy from each other. The consultant company AFRY has developed a *power market dispatch model* called BID3 which can make a prediction of the electricity market in Europe in the range of hours to several decades ahead. This model can help actors to decide when and from where to purchase electricity, as well as make prediction on how new transmission lines or large generators would affect the grid and the market. One disadvantage with BID3 today is that it does not include any transmission constraints within a country, i.e. it uses a *copper plate model* [1], and have a somewhat rigid model for the cross-border transmission.

1.2 Aim

The aim of this master thesis is to improve the performance and make the prediction of BID3 more granular by creating an alternative model that include network constraints and transfer limits within the country. This model will be based on the European Network of Transmission System Operators for Electricity (ENTSO-E) grid data, and to be able to utilize the data, it needs to be compatible with Siemens simulation software PSS/E. The network in PSS/E will be able to input BID3 data and process it to more accurate represent a national grid.

1.3 Problem description

By foregoing the copper plate model, grid constraints will emerge, and not only between countries and price zones but also within. Since the European grid is so large and even a small study of a single country and its cross-border power flow demand, large processing power and likely manually correction of the data in PSS/E, simplification of the grid is needed. In order to both be able to simplify the grid, and not change its properties too severely, it potentially has to be done in several iterations. Each iteration will merge more and more units by each step, thus gradually creating an equivalent reduced network. Due to the time constraints of this project, only the electric transmission system of Denmark will be reduced into an equivalent network in this thesis, as a proof of concept.

This master thesis can be divided into four parts, firstly to map the European transmission systems from the ENTSO-E data in CIM-format into the PSS/E compatible RAW-format. Secondly, adjust the RAW-data in accordance with a few important key hours (based on load and production data from BID3), and enable import of the Danish transmission system data into PSS/E. Thirdly, if possible solve the unaltered case in PSS/E and then create an equivalent reduced network. Fourth, and lastly, analyze the Danish grid in a reduced state and look at losses, the power flow, primarily cross-borders, and secondarily within Denmark itself.

1.4 Scope

This project will include an initial literature study regarding the European transmission system in general, and the Danish in particular, in order to become familiar with the field and previous studies. Further knowledge about the CIM-formats properties and structure will enable the conversion of the grid data to a PSS/E-compatible format. That conversion is also necessary for the creation of a simplified grid model of the Danish electric transmission system.

Even though some input data such as load and generation patterns will be delivered from BID3, the ultimate aim of this thesis is to improve BID3. No actual work will be performed in this program within this project, but rather to process the BID3 output data to see if it can be improved. As previously mentioned only the Danish electric transmission system will be model (due to time constraints). It's nonetheless well suited for this as it is relatively small, is located in the outskirts of continental Europe. Thus it should be more manageable to analyze, calculate and overview power flow, production losses and the number of nodes. The decision was made to only look at a few hours and not the entire year, this limitation was made both due to limited processing power, only access to one PSS/E v35 license and time.

2
Background on the European grid

Most of the national transmission systems in Europe are connected through some form of transmission line, thus forming the European grid. In this chapter an introduction is given regarding this grid and how the grid is organized. Then continuing by describing how the electricity market functions followed by some of the challenges facing the European grid and thereafter a section is dedicated to this thesis test case country: Denmark. Lastly, the chapter is concluded by giving a brief explanation of some key technologies used in the grid.

2.1 Governing body

An Internal Energy Market (IEM) is being developed within Europe through market integration which requires the rules of cross-border markets to be harmonized [2]. This is the purpose of the Network Codes and Guidelines (NCG) governing cross-border electricity networks and the trade of electricity [2], [3]. The third energy package was therefore introduced by the European Union (EU) in 2009 which lays out how the NCGs should be developed. NCGs are implemented by the European commission with input from the European Union Agency for the Cooperation of Energy Regulators (ACER) and ENTSO-E [4].

ACER is an EU decentralized agency with the purpose of helping build the IEM by monitoring the progression. It has the authority to make decisions regarding cross-border issues when necessary [5]. The ENTSO-E is a collaboration between 42 transmission system operators (TSO) from 35 European countries whose objective is to develop and maintain a functioning IEM as well as supporting the European energy and climate agenda [6]. Following the introduction of the EU 2020 objective, ENTSO-E was founded in 2009 by EU's Third Legislative Package for the Internal Energy Market. European TSOs had previously only had a voluntary collaboration regarding transmission in the form of a forum but when market related issues started being discussed, as a result of the increased liberalization, it was realized that enforced cooperation was required [7]. Members of ENTSO-E are divided into five synchronous areas (SA), the Continental European-, Nordic-, British-, Irish- and Baltic synchronous areas [8]. A SA has a synchronized grid frequency and can be connected to another SA via direct current (DC) interconnectors. The SAs are shown in Figure 2.1 [9].

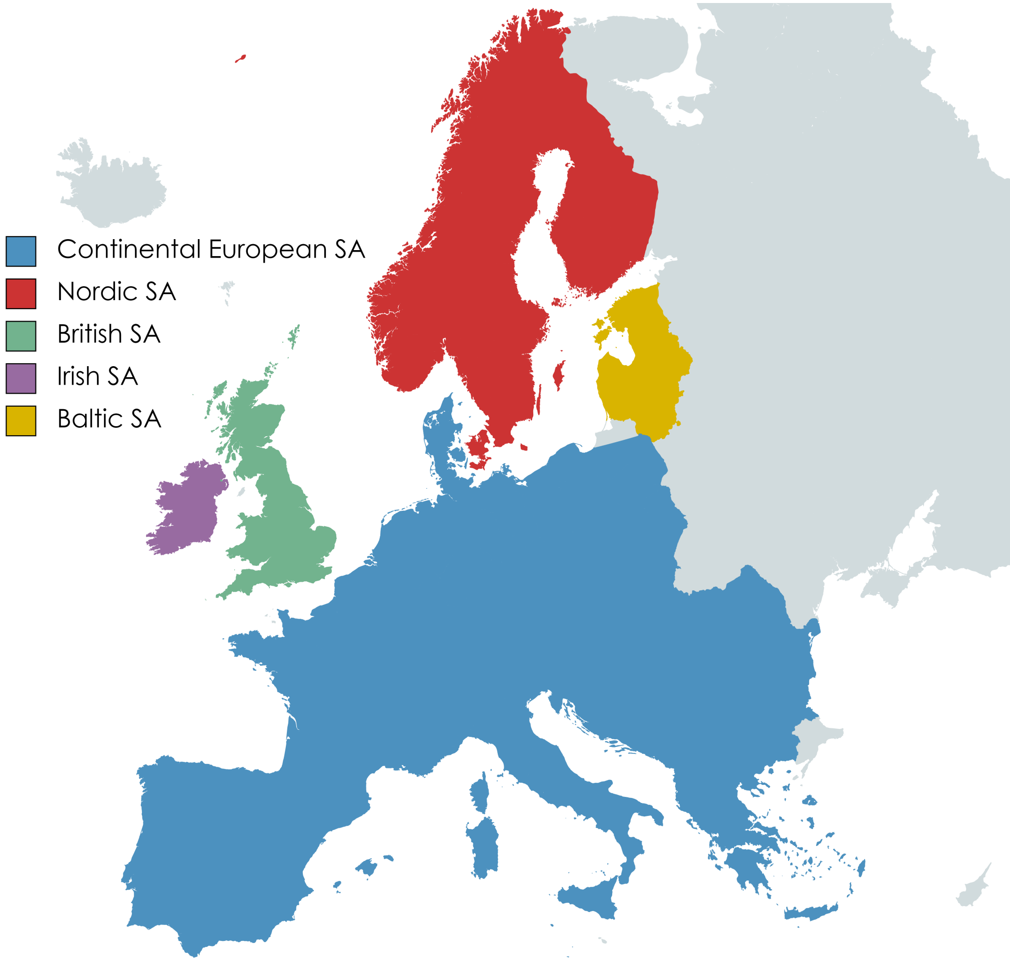

Figure 2.1: Synchronous areas containing the members of ENTSO-E

Turkey is an observer member of the Continental European SA while Cyprus and Iceland are their own isolated systems. Being part of a synchronous area gives the advantage of having a larger source of production which lowers the cost of generation and reserves. In the organization of ENTSO-E, the synchronous areas are called regional groups and each one works to, among other things, find the causes of internal disturbances and system integration within the group as well as with the other groups. Worth underlining, as seen in Figure 2.1, the Baltic states are isolated. This is due to the fact that they are electrically connected and synchronized with the Russian and Belorussian SA [10], i.e. UPS/IPS (Unified Power System of Russia/Integrated Power System) [11].

2.2 The European energy market

Trading with electricity is different from trading with other goods because of the difficulties of storage, limitations in transmission and demand is highly fluctuating [12]. In the EU, the market sees the European grid as a collection of bidding zones between which there are transmission limits. The market does however not consider any limits of transmission within a bidding zone, it is seen as a copper plate [13], [14].

2.2.1 Time dependent markets

In addition to the electricity itself, transmission capacity has to be purchased if the electricity is to be transmitted between bidding zones [12]. This results in that there are several markets for electricity which are open at different times ahead of the time of delivery .

The forward markets can open years in advance and may continue until one day before the time of delivery [12]. During this time cross-zonal transmission capacity is sold separately from electrical energy. In addition to these two types of markets there is also a forward balancing capacity market where balance service providers sell electricity to the TSO, who is also the organizer of this market [13], [15]. This market is active from one year until one day before the time of delivery.

Closer to the time of delivery, the Day-ahead markets (DAM) and Intraday markets (IDM) are held, as their names suggest, one day before and the actual day of delivery respectively [16], [15]. The day-ahead market is an auction where electricity and cross-zonal transmission capacity is purchased collectively. The intraday markets however, varies between countries and close at a specific time prior to the time of delivery called *Gate closing time* [15]. Lastly, the balancing market for energy is a market where the TSOs purchase power in real time by asking the balancing service providers to change their production or consumption. Each of the set of organized markets are covered by a network code or guideline except for the forward energy market. In addition to organized markets, transactions can be conducted directly between two parties [17]. This is called over-the-counter trading [18], and is most common for long-term contracts.

The DAMs and IDMs has an institutional framework in the form of nominated electricity market operators (NEMOs) which organizes trade across bidding zones [19], [14]. In the EU, the TSOs are designated by the competent authority of a member state, the state is required to ensure that their is at least one NEMO organizing the DAM and IDM in that state [20]. The for-profit institutions EPEX Spot SE and Nord Pool EMCO AS are designated as NEMOs in the highest number of countries for both the DAMs and IDMs [15], although they do not have monopoly anywhere for neither DAMs nor IDMs [19]. On the other hand, some countries have their DAM and IDM monopolized.

2.2.2 BID3

The consultant company AFRY has created a simulation software called BID3, and is used as a power market dispatch model. BID3 has several features and can be used in a wide range of applications, but it is primarily focused on electricity price. The attribute, that is central for this study, is the dispatch model used to simulate supply and demand of electricity [21]. Closely related to the simulation of supply and demand is the ability to analyze how integration of Renewable Energy Sources (RES) in a electric grid, as well as the economic aspect of the grid and how the electricity price may change over time.

One of the applications of BID3 is to predict how the power market will develop and is used by electricity producers, regulators and TSOs [21]. One drawback however is the way BID3 represents each electric zone or country. They are all seen as a conductor with infinite capacity, a so called *copper plate* [1]. This simplification disregards congestion, local bottle necks and can be very inaccurate in regards to line losses [22]. With increasing amount of RES in the European grid, the copper plate model may become less reliable, e.g. local or regional congestion in the case of very favorable wind for Wind turbines. The challenges of the European grid, for example loop-flows and the congestion in Germany [23] only emphasizes a less rigid representation of the grid than the current copper plate-model may be needed.

2.3 Challenges in the European grid

As one of the largest transmission system in the world [24], the European electrical transmission grid faces several challenges both today and in the near future [25], [23]. One of the underlying problems is that the European grid was not originally built as an interconnected Pan-European piece of infrastructure, but as several small, and in varying degree, self-sufficient national transmission networks [24]. In the last three decades major political changes have occurred, from the fall of the Soviet Union to the rapid expanse of the bilateral European cooperation, EU, and the electric transmission system has not always been able to keep pace.

2.3.1 Congestion

The degree to which the European countries are interconnected varies greatly, and examples of limiting factors are of course political history and geopolitics, technology, geography, and industrialization. For example, the high interconnectedness between the Czech Republic and Slovakia is a remnant from when they were both part of Czechoslovakia [25], and the poor interconnectedness between France and Spain is partly due to geography and partly due to political history. Low transmission capacity between two countries is not the only reason for congestion, the lack of transmission capacity within a country can also give rise to congestion. One example of this is the low transmission capacity from the northern part of Germany to the southern part. Whatever the reason for a sub-optimal regional transmission system, the consequences are still there and results in, among other things, loop-flows [25].

2.3.2 Loop-flows

Loop-flows occurs when the need for electricity transmission from area A to B is larger than the capacity and therefor the power flow takes detour, in this case through area C as illustrated in Figure 2.2.

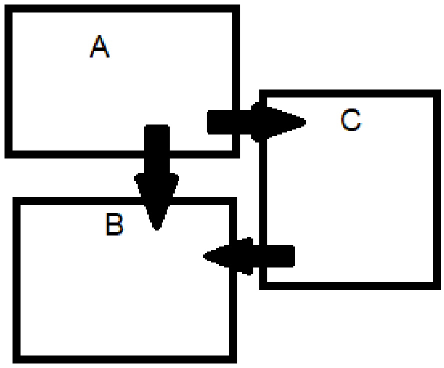

Figure 2.2: Illustration of loop-flows

With the phase out of the nuclear power, at least in part due to the Fukushima accident in 2011 [26], Germany have to supply its citizens and industries with electricity from elsewhere. Traditionally, coal power has been the go-to alternative as a complement to nuclear power, but an increase in coal power or other fossil fuel bases power generation is in conflict with Germany's international environmental commitments, i.e. not an option [27]. Therefor a even larger share of RES is expected in the coming decades for Germany [28], [29].

In the last couple of decades, the amount of wind power in the north of Germany has increased dramatically and this has in part helped to mitigate the otherwise electricity shortage in the southern part of the country [23]. This large-scale power transfer from the north to the south has pin-pointed to another problem: congestion in the transmission grid and this in turn has given rise to loop-flows [25], [30].

The loop-flow phenomena has been observed in, among other places, Poland [30] from its cross-border connection to Germany. In Figure 2.3 one example would be that needed power transmission from 50Hertz (Germany) to APG (Austria) is larger than the transmission capacity via TenneT, therefor the power will also flow via PSE (Poland) and ČEPS (Czech Republic), thus creating a loop flow.

Figure 2.3: Map of Central Europe and the approximate area of each TSO area of operation.

This may also lead to additional problems and in the worst case to a large blackout such as the Italian blackout in 2003 [31], where the problem started in Switzerland, i.e. out of the jurisdiction of the Italian operators. In 2003, which still holds true today [32], [33], Italy imported a large share of its electricity, among others via Switzerland [34]. When a fault occurred in the Swiss grid, which subsequently caused several transmission lines to disconnect, first inside Switzerland itself, which made Italy supply parts of Switzerland. Causing increased import from primarily France in a fast manner, leading to a rapid drop in voltage, thus disconnecting even more transmission lines. Right before these events 26 % of Italy's load was supplied with import (mainly from France and Switzerland) [34]. All of this added together resulted in the large blackout in 2003 [31], [34].

Italy and the west alpine region is also another example of the occurrence of loop flows. Since Italy is importing much of it's electricity [32], [33], and the transmission lines to France, where most of the import is taking place [35], is already close to their capacity limit the transmission system in bordering Switzerland is affected [31], [35]. An Italian study [36], showed that in a base case only 39 % of the electricity produced in France and consumed in Italy was actually transmitted via their borders. The rest resulted in loops involving Belgium, Germany, Austria, Switzerland and even

Slovenia and the Netherlands [36]. This gives rise to additional, unnecessary, strain on the Central European transmission system. E.g. Poland has stated to implement phase shifting transformers, (see Section 2.5) in order to try and mitigate the loop-flows caused by the congestion in Germany [30].

2.3.3 Electricity generation location

A subsequent problem of a large share of renewable energy sources in the European grid is that the existing infrastructure is not built for neither a decentralization, as a result of a high number of small scale photovoltaic (PV) system, nor designed to manage large amount of intermittent power generation from for example wind power. It is very seldom a large wind power farm can be built in the same area as a decommissioned nuclear or fossil fueled power plant. On top of this the challenge of electrifying the vehicles of Europe still looms over the European TSOs.

PV and wind power generates different challenges for the power system. PV are often, at least in central and northern Europe relative decentralized and do not generally connects to the power system at the same voltage level as Wind power (WP) [37], [38]. This problems can be addressed by either reinforcing the power system by additional transmission lines, or to some extent by the implementation of Energy storage systems, e.g. batteries. The problem that Germany faces is not a lack of generation capacity, but one of transmission from the large wind farms which gives rise to this very phenomenon [39], [25], as mentioned in Section 2.3.2.

2.4 Denmark

Denmark has one of the largest share of renewable energy production in the EU [40], and what is worth pointing out is that in the past 30 years Denmark went from under one percentage PV and WP to close to 50 % [41]. Placed in between the Scandinavian peninsula and continental Europe this not only affects the country's geopolitics but also its energy policies. In terms of transmission system Denmark is split in two, as seen in Figure 2.4, the western half with mainly Jutland *(sv. Jylland)* is part of Continental European SA and Eastern part with mainly Zealand is part of the Nordic SA [9].

Denmark is a good candidate to be a test case for managing the ENTSO-E transmission system data. Since Denmark is a small country, both in size and population, but is very well-developed and connected, yet has relatively few transformers, buses and other infrastructure units, it is a good test case. The country is also remarkably interconnected via its various AC and DC links to the Netherlands, Norway, Germany and Sweden [42], but is still in the relative periphery of the European transmission system. I.e. Denmark is a suitable test case as it is a good trade of between, size, complexity, interconnectedness and power flow.

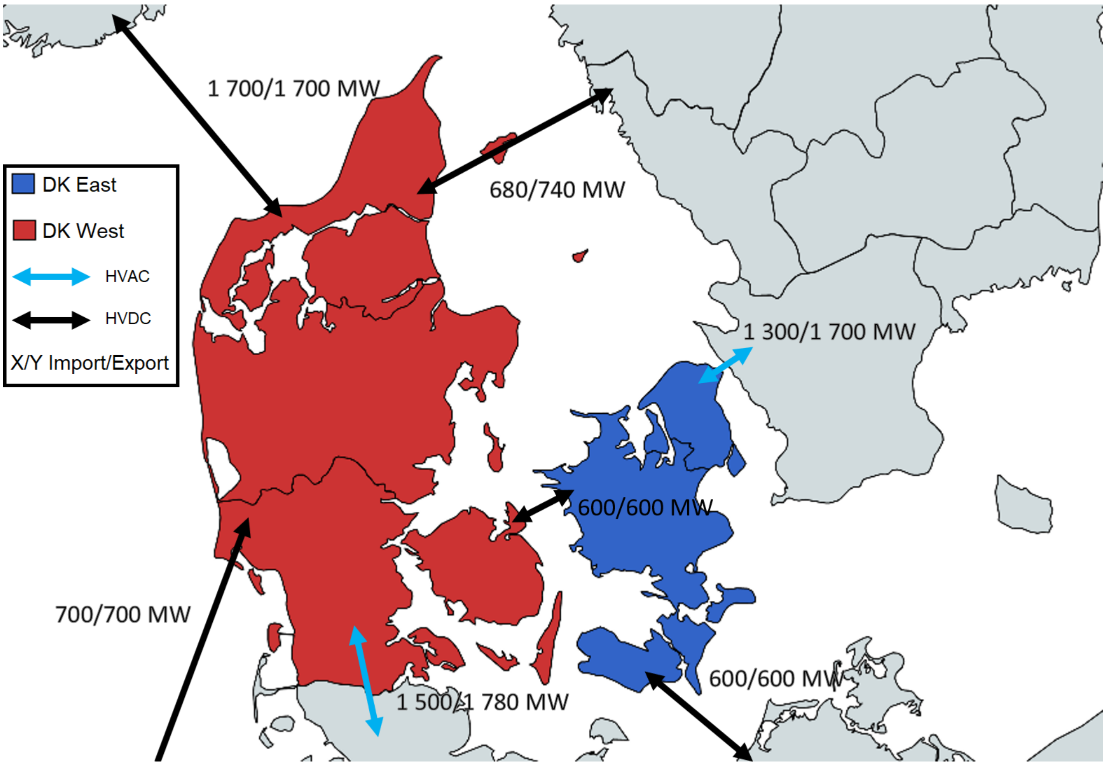

Figure 2.4: Map of the Danish Electricity zones, and the cross-border connections and their capacity limits in 2019 [43]

By both being a small country and with a large share of RES, it is important for Denmark to be well connected with its neighboring countries. Large transmission capacity makes it possible for Germany to utilize the relatively cheap and clean hydro power from Norway and Sweden. At the same time both Denmark and Norway benefits from the possibility for Denmark to export excess wind power to Norway, which then can use the excess electricity in its pumped hydro reservoirs [44]. As of 2019 Denmark has an high voltage direct current (HVDC) cable to the Netherlands of 700 MW, 1,700/1,700 MW to Norway and a mix of HVDC and AC lines to Germany 2,500/2,780 MW [45] (planed to expanded to 4,500/4,500 MW in 2023 [43]) and 1,980/2,440 MW to Sweden (the island of Bornholm not included) [43], illustrated in Figure 2.4.

The Danish transmission system is operated by its TSO, Energinet, and Energinet is also responsible for the stability of the system. As both a well developed country with high-tech industries, and as a connection node between Scandinavia and continental Europe, it is important do have a robust electric system with no losses. In 2018 the total losses of the transmission system was estimated to up to 2.5 % of the consumption[46], [47], [48], and the total grid losses, including the distribution system 6-10 % [49], [50].

2.5 Phase shifting transformers

In three-phase systems the phase shifting transformer (PST) can be implemented to control that active power flow between electric grids [51]. The equation for active power flow (P) over a lossless line is

$$P = \frac{|V_S| \cdot |V_R|}{X_L} \cdot sin(\Psi) \tag{2.1}$$

where V_S and V_R is the voltages at the sending end and receiving end respectively, X_L is the line impedance and Ψ is the transmission angle. The transmission angle is the difference in phase angle between the sending and receiving end which can be regulated by a PST located at the sending end by adding phase angle difference (ϕ) between the voltages of the first and second winding [52]. The equation for the active power flow becomes

$$P_{PST} = \frac{|V_S| \cdot |V_R|}{X_L + X_{PST}} \cdot sin(\Psi + \phi) \tag{2.2}$$

where X_{PST} is the reactance of the PST.

This enables the system operator to prevent lines from becoming overloaded by shifting the power flow to a parallel line [51]. Furthermore, PSTs can be implemented in order to the counteract the problem of loop flows which has been done on the Polish-German and Czech-German borders where it lead to a substantial decrease in unscheduled power flows [53].

Phase shifting transformers are either symmetrical or asymmetrical depending on the their ability to control reactive power flow [54]. For two-winding symmetrical PSTs the voltage magnitudes at both windings are equal regardless of the phase angle difference imposed. Asymmetrical PSTs however, alters the voltage magnitude at the secondary winding ($|V'_S|$), allowing it to control the reactive power flow (Q) now given as

$$Q_{PST} = \frac{|V'_S|}{X_L} \cdot (|V'_S| - |V_R| \cdot cos(\Psi + \phi)) \tag{2.3}$$

This is because of how the PST controls off-nominal turn ratio (t), which is defined as

$$t = \frac{|V_S|}{|V'_S|}) \tag{2.4}$$

and is given as

$$t = \frac{sin(\alpha)}{sin(\alpha + \phi)} \tag{2.5}$$

if $\alpha \neq 0°$, where α is the winding connection angle of the PST. A quadrature booster transformer, which is widely used, is an asymmetrical PST where $\alpha = \pm 90°$ which simplifies the expression for the off-nominal turn ratio into

$$t_{qb} = \frac{1}{cos(\phi)} \tag{2.6}$$

2.6 HVDC transmission lines

Traditionally a transmission system consists of a number of units connected to bus bars with transmission lines in between and everything is supplied with AC. This is still mostly correct but there are several cases where HVDC links are preferable, e.g. long distance sub-maritime cables, interconnected asynchronous transmission systems and for long distance transmission. Today there are over 100 operational HVDC installation in the world [55], and with the continued technological breakthroughs in power electronics more applications are likely to come [56]. Simplified, an HVDC-transmission line in an AC-transmission system can be broken down into three main part: i) a converter from AC to DC, ii) the DC-transmission line itself and iii) a converter from DC to AC. The converters can of course be categorized further into rectifiers, that converts AC to DC and inverters that converts DC to AC.

In the case of long transmission lines, traditionally AC-transmission lines are more expensive than HVDC-lines for distances greater than 640 km with the same voltage level [57], [58]. One of the reasons is that since AC by definition has a frequency and DC does not, the resistance in a AC-transmission line is higher than DC due to the Skin effect [57]. HVDC-transmission can also be beneficial to the surrounding area in terms of less electromagnetic interference (EMI) and the Corona effect is also less prevalent than comparative AC-transmission lines [59].

3

Data input and processing

This chapter gives a brief overview of the data formatting that was carried out in this thesis, i.e. to convert the data from ENTSO-E in CIM-format to the PSS/E comparable RAW-format. The focus is on how each format is structure and the challenge in going from one format to the other, when the data structures are so different.

3.1 Data processing steps

This section aims to give the reader a overview of the different steps and components that enables this thesis results. To summarize the work process and data processing for this entire thesis, Figure 3.1 gives a fairly good overview. The input data can be categorized in three different groups:

1. Time specific data, such as production, load, cross-border power flow and price of electricity for almost all member countries in ENTSO-E. This data was delivered by AFRY and was the output of their program BID3. BID3 in turn utilizes primarily open-source data from ENTSO-E, various TSO and Distribution system operator (DSO) in Europe.

2. Data of the entire European electric network, complete with generators, load, transmission lines, transformers, shunts, etc. All that data was delivered by ENTSO-E and was in a CIM-format.

3. Recorded data of cross-border power flow from ENTSO-E Transparency Platform

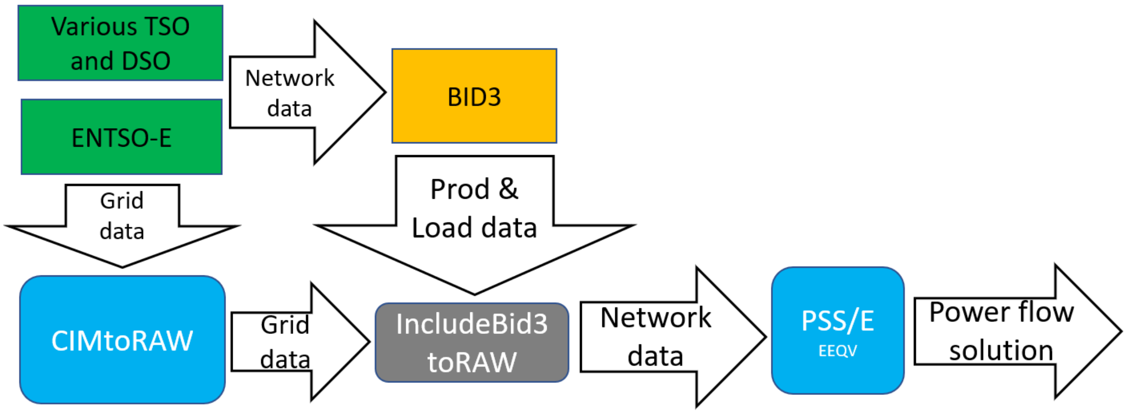

Figure 3.1: Illustration of the origin of different types of data and how they interact with each other. Green boxes are different data sources that has been used in this project either directly or indirectly. The CIMtoRAW converts the data from the CIM-format into a PSS/E compatible RAW-format. The dark gray box *IncludeBid3toRAW* is a script that implement the BID3 data into the RAW-file, for the different load cases (see section 4.1.1 for more details). The cases are then imported into PSS/E where the simulated power flows and network reductions are performed.

The first step is to convert the data from CIM to the PSS/E compatible RAW-format, more detailed information of these two formats can be found in Section 3.2 and 3.3. The second step is to identify a few key load and production hours to investigate more closely. This is due to the simple fact of the sheer amount of data for an entire year for a national electric system. Section 4.1 gives a detailed account of the process and the hours selected for further analysis. When the hours are selected the data, now in the RAW-format, needs to be altered to coincide with the load and production data from BID3. The third step is to input the data into PSS/E, try to solve the case, and then in several iterations reduce the network to create an equivalent network. This step is discussed further in Section 4.2.

3.2 CIM

A necessity for cooperation and be able to interconnect two electric transmission system is that the operators communicate in the same language. In this case, that the grid data has the same data format or can be converted without severe information loss from one TSO to another. One of the most used data models for power systems in the Common Information Model (CIM). CIM can mainly be derived from IEC 61970-301 [60] and ICE 61968-11 [61]. This is the data format used by ENTSO-E for mapping and modulating the European transmission system.

3.2.1 Data format

Without delving too deep into the field of data science and data structure, it is important to understand that CIM uses a number of different classes to store different categories of information. All classes are not equal in the system, some classes are defined as a sub-class to another class [62]. In that case the sub-class inherits all attributes of the *parent*-class [63], e.g. as in Figure 3.2.

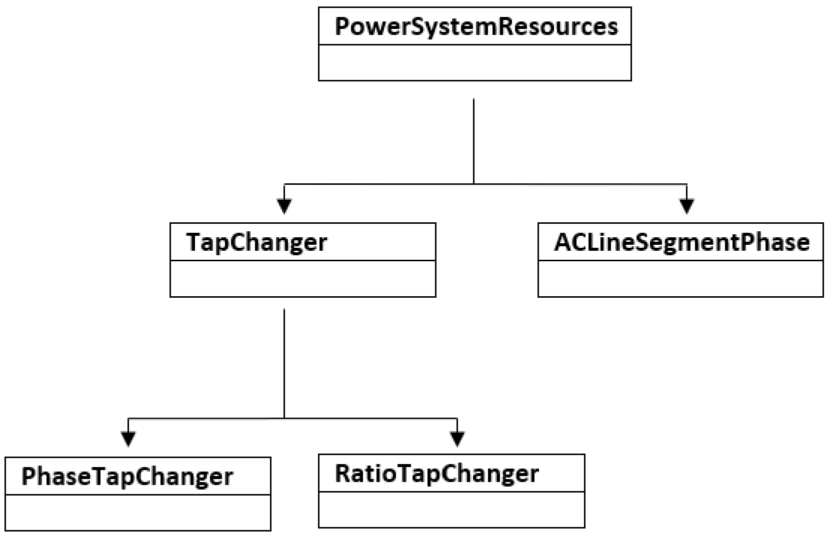

Figure 3.2: Exemple of the data structure within CIM, with classes and sub-classes

In Figure 3.2 both PhaseTapChanger and RatioTapChanger are sub-classes to TapChanger and therefore also inherits its attributes, but in addition both PhaseTapChanger and RatioTapChanger may have additional unique attributes that neither the parent class nor the *sibling* sub-class have [62].

Regardless of class every object element has a unique Master Resource Identifier (mRID) and is a very useful property when evaluating and converting the data from CIM to another data format [62]. For example, when converting power system data from CIM to the simulation software PSS/E one must make sure to check each mRID in each class to determine what other class it is related to. In PSS/E transmission lines, loads, generators, and transformers are connected to busbars with sequence numbers, this is not the case in CIM. Therefore, it takes extensive mapping of the CIM formatted data to not only make sure which pieces of infrastructure are connected, but also how to access a units specific data and store it in a PSS/E compatible way. Finally not all information that relates to a specific type of unit are stored at the same place, i.e. CIM do not uses a thematic information storage system. For example not all information and data related to TapChangers is stored in some of the sub-clases to TapChanger. There is also data in subclasses to Equipment, among others TransformerWinding, which is a subclass to ConductingEquipment, as seen in Figure 3.3.

3.2.2 Packages and structure of CIM-classes

The CIM data structure is organized by the basic three main packages: Core, Wires and Topology [62]. In short the Core packages contains the classes that relates to units in a power system and their properties such as, base voltage, transformer winding, generator data. The Wires package includes the objects that conduct electricity in a network, not to be confused with the Core class ConductiveEquipment that represent the conduction of electricity within an object itself [62]. For example, the wires that makes up the winding of a transformer is stored in Core, but the wires that makes up a transmission line is found in the package Wires [63]. Lastly Topology is a package that, as the name implies, stores the topology of the system. In essence one can determine how a unit is connected in CIM with information in Topology, some additional information from the Terminal class (in the Core package), and also one need information of the conductors that belongs to the package Wires [62].

3.2.3 Branches

What is referred to branches in PSS/E [64], is divided into ACLineSegment, EquivalentBranch and SeriesCompensator in CIM [63]. The most used class of these are the ACLineSegment. In ACLineSegment the attributes of the line itself are stored such as suceptance, conductance, resistance, thermal limit, reactance, length and mRID, but not the line voltage [62]. That piece of information is stored in BaseVoltage which is a Core-class.

3.2.4 Transformers

Transformer is a good example that data in CIM is not sorted in one class based on what unit it belongs to, or a *thematic* sorting, e.g. one class for each type of transformer, but it is rather based on the themes of the properties itself [63]. E.g, both VoltageLevel and TransformerWinding are sub-classes to ConductingEqutment, as seen in Figure 3.3, but they contain information that is needed to represent a physical transformer even though they are not a sub-class to TapChanger [62]. The attributes that are unique properties for a specific type of transformer are stored in the sub-classes of each type of transformer, e.g. PhaseTapChangerAsymmetrical.

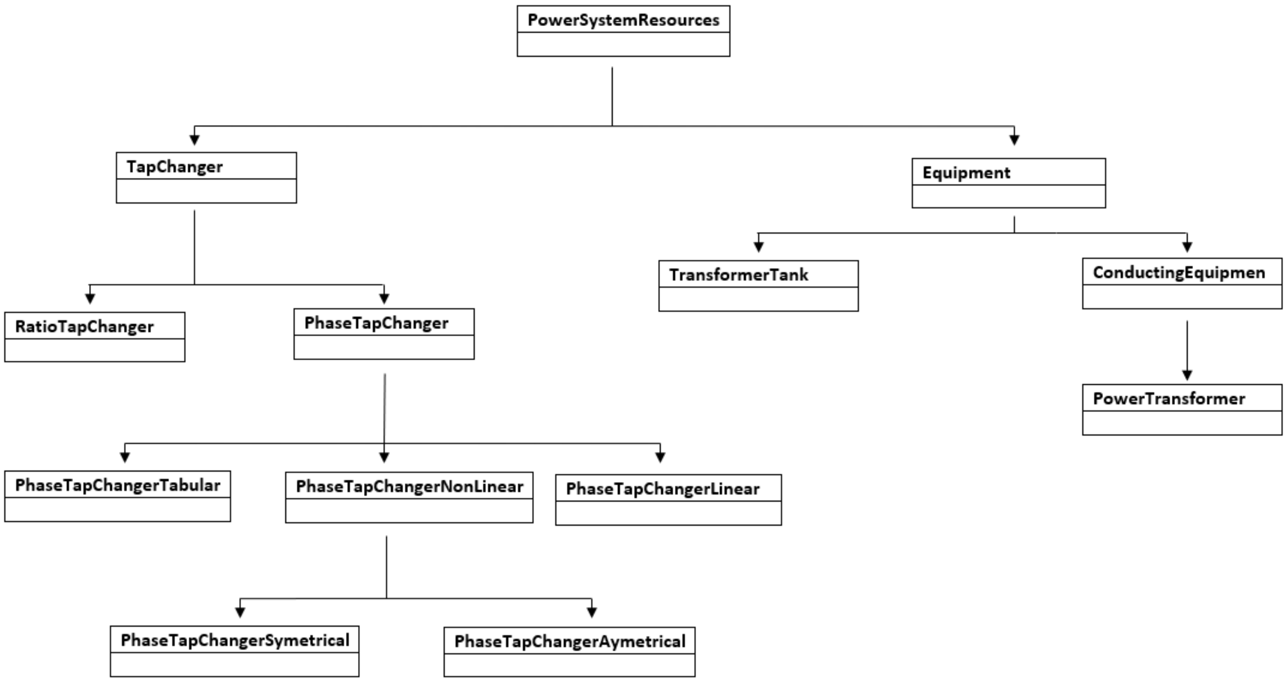

Figure 3.3: A hierarchical mapping of some of the transformer data in CIM, with their classes and sub-classes with their relations to each other, and a few side classes as examples [62].

Other essential information, as mentioned in Section 3.2.2, such as base voltage, where the transformer is located, properties of the substation itself of which the transformer is part of are stored in various other classes and packages [62].

3.3 RAW-format

In contrast to the CIM data format PSS/E uses a more *flat organization* to manage its data. In the RAW-format almost all of the data that relaters to a specific unit or type of equipment is stored in one place. Some information may be found elsewhere, for example what zone a specific generator is placed in. That information must be sought after via the bus that the generator in question is connected to. With that in mind, this format could be seen as easier to organize smaller networks than the more decentralized and sometimes overwhelming cluttered CIM-format.

There are in total 23 different types of RAW format groups or record format [64]. For each of these 23 record formats different information is stored in a long list, and it is of out most importance that the information is stored in the correct place and that the information is sorted in the right order within the list. Below is an example of the RAW record format of Bus Data:

I, 'NAME', BASKV, IDE, AREA, ZONE, OWNER, VM, VA, NVHI, NVLO, EVHI, EVLO

Where I is the bus sequence number, 'NAME' if the name of the bus, BASEKV is the base voltage in kilovolts, IDE is a bus code from which the system can read what kind of bus it is, e.g. 1 is a load bus, 2 a generator bus, 3 a swing bus, to mention a few properties of the RAW-format. The same structure is used for the other 23 record format. Some variables are more important than others and this is briefly touched upon in 3.3.2.

3.3.1 Case Identification Data

One set of data in the RAW-file that is very important but do not refer to any specific typ of unit within the network, but rather to the system as a whole. It is also the first set of data that PSS/E reviews when opening a RAW-file: *case Identification data*. It is a CSV-list of a total of 8 data items that tells PSS/E what kind of data that follows. It is spread out over three lines and are:

@!IC,SBASE,REV,XFRRAT,NXFRAT,BASFRQ

Which in turn are: @! declares the beginning of a new section, such as Case Identification, bus, transformer, or shunt data. It do not show in the PSS/E file presenter window, but if one opens a file in a CSV-reader those symbols appear. IC is 0 for a new base case, i.e. it will clear the previous working case in PSS/E before adding in the new data from this RAW-file, or 1 for an existing case, i.e. it will just add the data. Sbase is of course the systems base of apparent power, Rev the revision number of PSS/E, i.e. the version of the software (this thesis worked in PSS/E version 35). XFRRAT relates to the rating of transformers, while NXFRAT to the rating of non-transformer branches. Lastly BASFREQ is the system frequency. All of this is on vital importance in order for PSS/E to read the RAW-file in the correct way.

3.3.2 Key data variable

Beside the most obvious that a unit's physical attributes such as resistance, base voltage, connected to the correct bus and so forth, there are several key variables. These key variables that are of the out most importance in order to be able to solve the case, at least for this thesis, and create an equivalent reduced network.

One striking difference between CIM and RAW-format is the impedance of a two-winding transformer, and more precise how it is represented. In CIM-format the impedance on the high voltage side is none-zero value and on the low voltage side the impedance is zero [62]. No regard is taken to what side the tap-changer is located (if the transformer is a tap-changing transformer). In PSS/E, i.e. in RAW format the two-winding transformer total impedance is stated, and the tap-changer is always located on the primary side. A way to address this is to work with the impedance in per unit (pu), if looked at Figure 3.4, the reactance is

$$X_1^{pu} = X_1 \cdot \frac{V_1^2}{S_{base}} \tag{3.1}$$

then one can reconvert the reactance on the secondary side by multiplying with Z_{base}

$$Z_{base} = \frac{V_2^2}{S_{base}} \tag{3.2}$$

thus representing the correct value and store it at the correct place in a data format. This is very important to verify that these factors are correct in order to model a grid correctly.

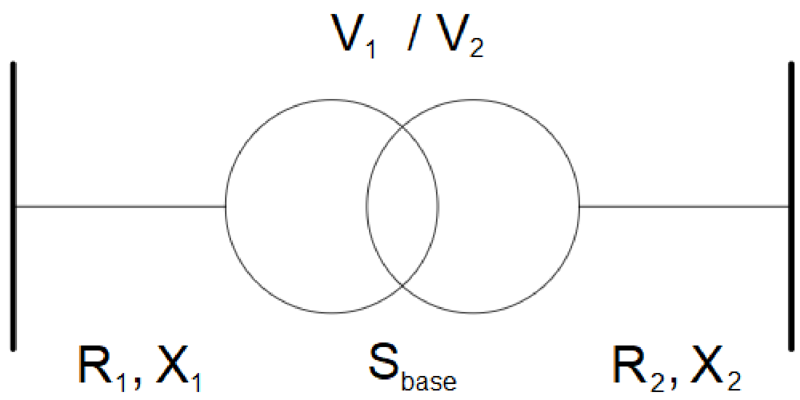

Figure 3.4: Representation of a transformer connected between two buses. Left side with variables with subscript 1 is the primary side, and the right side with variables with subscript 2 is the secondary side.

As mention in section 3.3 in regards to the bus data, AREA determent what country the bus is located in. In the data there are two areas, one for Denmark and one set of fictitious ENTSO-E buses, which are there for facilitate analyzing the grid. These buses are called X-buses and are place on every border crossing in the entire European grid in the ENTSO-E CIM data set. To get this right is extremely important if one wants to study cross-border flow, or create a reduced network via the EEQV function in PSS/E. EEQV is a built-in function in PSS/E that create an equivalent (reduced) network from a solved case.

Another key variable in the bus data is to make absolute sure that the IDE is correct. If IDE is not correct and tries to perform the EEQV function in PSS/E, the grid doesn't get reduced at all, or wrongly so. Additionally if one needs to keep a number of selected buses, e.g. would like to keep a large wind farm unaltered, than the IDE needs to be manually altered. If the IDE is not correct to begin with it is unlikely to choose the correct EEQV-adjusted IDE. More on how IDE affects EEQV can be read in section 4.2.

Lastly, the correct classification of type of generator and load is also important when converting from CIM to RAW. Because when trying to scale load and producing up or down in accordance with the BID3 data for a certain hour, then if could have large consequences locally in the grid if for example a large thermal power plant is identified as a wind park. More on how this is done and the difference between ENTSO-E, BID3 data and data from the Danish TSO can be found in section 4.1.1 and 4.1.2.

4

Network simulation and power flow analysis

This chapter fist contains an exposition of how the selected hours within a year has been selected, then follows a subsection on how the BID3 data has been implemented in the grid, which the ENTSO-E data describes, and also an inquiry on the validity of the production data compared to actual recordings from the same year. The second part of this chapter is dedicated to the work in PSS/E. How the data was managed to make the case solvable at all, how the PSS/E creates an equivalent reduced network and lastly a comparison of the BID3 power flow predictions and the ENTSO-E historical records.

4.1 Load hours and BID3 integration

This section present the BID3 load and production data both for Denmark's two zones and of Denmark as a whole. From the load and production data, four case hours are identified for further processing and simulation in PSS/E.

4.1.1 Load data

In order to choose hours of high interest for Denmark one has to look at the load curve i.e. the demand of electricity for each hour. In Figure 4.1 and 4.2 all hours from 1^{st} January to 31^{st} December in 2019 are presented in chronological order, both for each separate zone, and for the total of Denmark. By choosing a few key hours based on the load for that hour, this can be used as input load data and basic generation data into the PSS/E and compare the power flow to both the predicted power flow from BID3, and the actual recorded power flow.

In Figure 4.2 the total load and production in Denmark presented, i.e both DK West and DK East combined. From the figure it is clear that there are still fairly large load variation and also the seasonal variation, with lower load in the summer months, as expected. Furthermore the large fluctuations in the power production is worth noticing, also expected as the Danish energy mix has a very high level of RES [41].

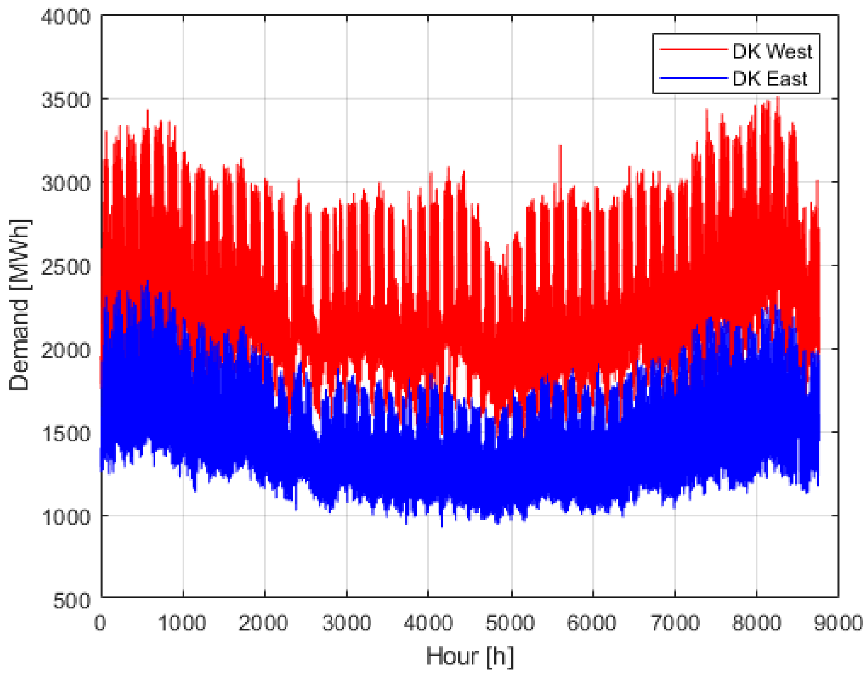

Figure 4.1: The amount of electricity demand for every hours in DK East and West for the year 2019

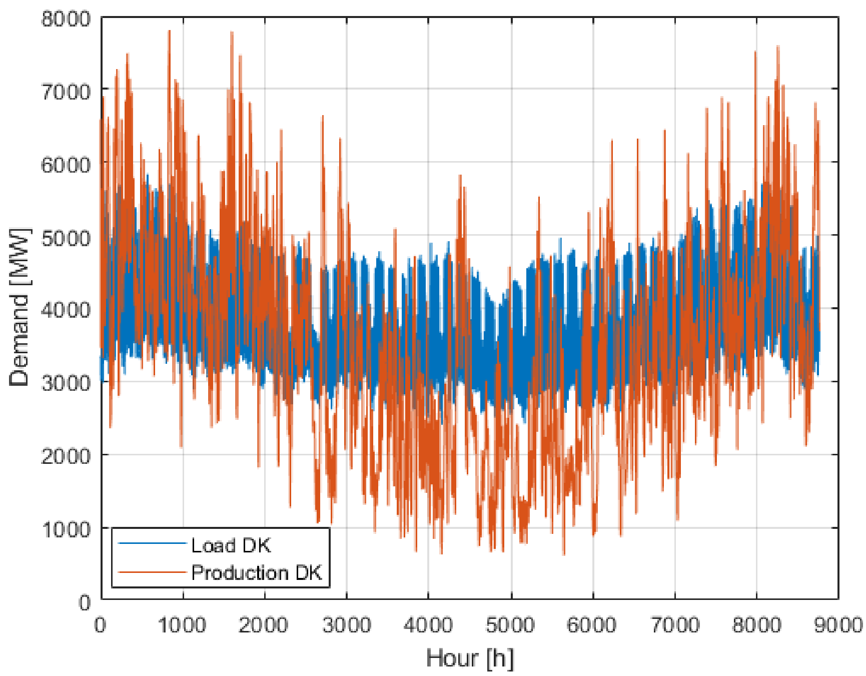

Figure 4.2: The amount of electricity demand and production for every hour in Denmark, i.e. the sum of east and west, for the year 2019

For a better overview of highly fluctuating data, such as load and production data, a common method is to sort the data from the highest value to the lowest, i.e. a duration curve. This curves makes it easier to identify the base load and production, as well how much the demand varies throughout the year. In Figure 4.3, one can see that neither the demand nor the power production is constant, far from it. Even though the data in Figure 4.2 indicates it, the duration curve makes it clear that the production is much more volatile then the load and for most hours during a year the domestic production is lower than the electricity demand.

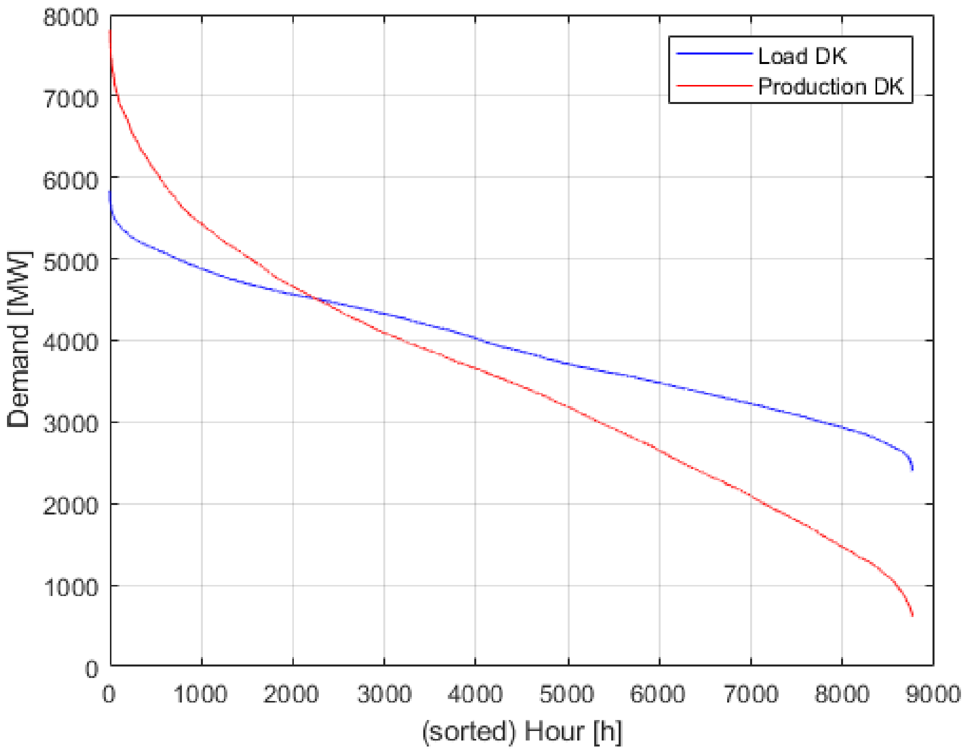

Figure 4.3: Duration curve of the total load and production of Denmark for the year 2019. Data is from BID3.

By combining the data sorted in Figure 4.2 and 4.3 different extreme cases for both the load and production can be identified. Four conditions were chosen:

1. High load and high production (HLHP)
2. High load and low production (HLLP)
3. Low load and high production (LLHP)
4. Low load and low production (LLLP)

For HLHP hour 834 was selected which was both at the top 1 ‰ for both load and production. For LLHP hour 2908 was selected as it (along with two other hours) was both found in the top 11 % of production and bottom 11 % of load. Hour 5771 was selected to represent HLLP as it was among both the top 14 % of load and bottom 14 % of production. Lastly, for LLLP the 4157^{th} hour was selected as it, (along with two other hours) was in the bottom 5 ‰ for both load and production.

When analyzing the energy mix for these four hours, as presented in Figure 4.4, it becomes clear that Denmark's heavy reliance on wind power has its drawbacks. Subsequently these cases, or load-cases, should be very suitable for studying the cross-border power flow, since they vary from high to moderate import and export of power.

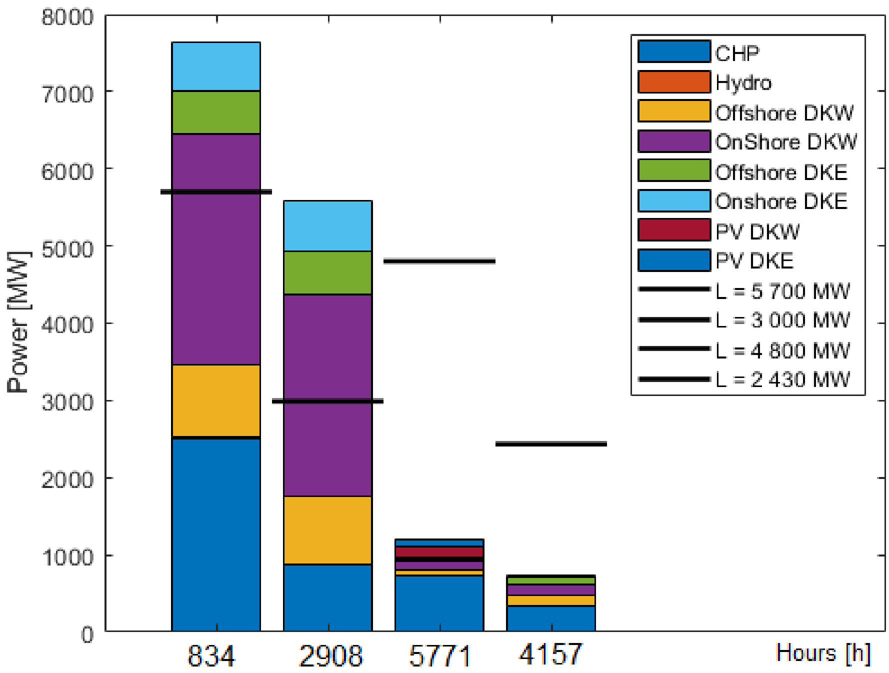

Figure 4.4: A stacked bar diagram, each bar contains the cumulative power produced in that specific hour. The thicker vertical lines, that either crosses or is above the bar represents the demand i Denmark for that hour.

4.1.2 BID3 and ENTSO-E data

One major and noticeable difference in the ENTSO-E CIM-data, compared to the BID3 data, is how the different types of production is categorized. When adding all the production for WP, PV, Thermal and miscellaneous, the WP and PV were fairly consistent, but the BID3 data had a much larger share of its total production in thermal than the ENSTO-E data. Therefore, the choice was made to scale thermal and miscellaneous electricity generation as one, i.e. thermal and miscellaneous are seen as one category and the production data for a certain hour will be sum of these two amounts.

Of course the generation capacity of the individual power plant will be the most important factor for the output, but how much the power plant will output of its maximum capacity is decided by how large of a share that its generation type produced in that hour, in that specific zone. To determine how much an individual generation should produce in a certain hour, firstly all of the production and capacity of this type of generation are added for each zone. The total maximum capacity of all generators of a type, e.g. WP, is calculated as

$$P_{max}^{WP} = \sum_{k=1}^{N} P_{max}^{k} \tag{4.1}$$

,where there are N wind turbine units. The sum of the total capacity within a zone is a summation of the total maximum capacity of all generators of each type, i.e

$$P_{max}^{Tot} \sum_{i=1}^{M} P_{max}^{i} = P_{max}^{WP} + P_{max}^{Misc+Thermal+PV} \tag{4.2}$$

where Misc, PV and Thermal generation units are seen as one type of generation. Note that here i is superscript for the identity of a specific power plant, and not suppose to be read as "raised to the power of i". This is due to a difference in grouping of the data between ENTSO-E and BID3. In the CIM data the Danish generation only consisted of WP, Thermal and Generation. WP was fairly straight forward to map between BID3 and the ENTSO-E data, but the rest had to be seen as one since the data from BID3 and ENTSO-E was too different, due to their own definition and mapping. Therefore, additional data was gathered from the Danish TSO, Energinet. Even though Energinet also had quite puzzling categorization of the different generation types, it was very useful to get an additional data set to compare the energy share. In Figure 4.5, each share of generation is presented, a) ENTSO-E CIM-data, b) BID3 data seen over 2019 and c) Energinet data seen over 2019.

When the total maximum capacity of all generators of each type, P_{max}^{WP} and $P_{max}^{Misc+Thermal+PV}$ is calculated the share of the individual power plan can be used and lastly multiply the share with the BID3 generation data for the specific hour h_0

$$P_{gen}^{k_1} = \frac{P_{max}^{k_1}}{P_{max}^{WP}} \cdot P_{BID3Gen}^{WP}(h_0) \tag{4.3}$$

where k_1 is the identity of a specific WP farm. The first fraction determent the share of the power plant, in this case the WP k_1, and this share of the total generation within the zone is then multiplied with the total generation of the type according to the BID3-data from a specific hour, h_0, i.e one the hours that were chosen in Section 4.1.

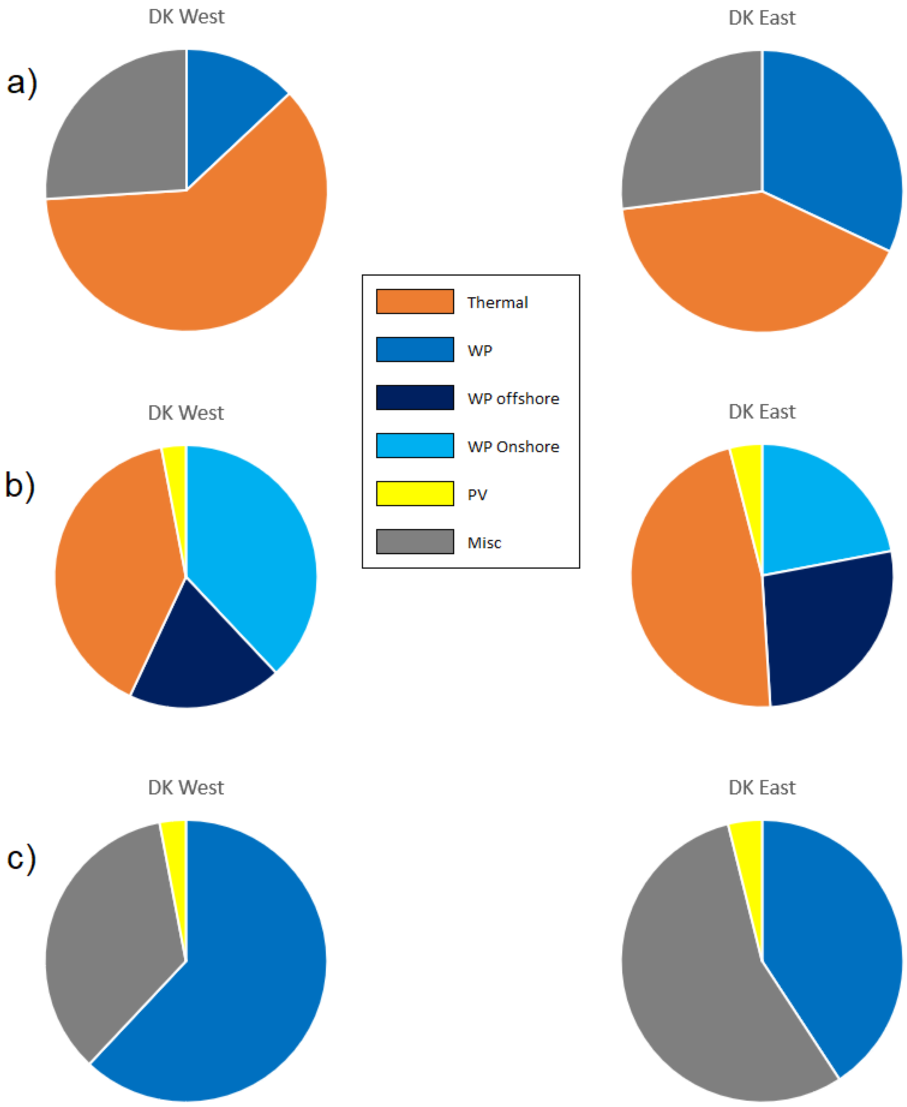

Figure 4.5: Pie charts of share of production in DK East and West. a) The default P_{gen} from the ENTSO-E data. Misc here refers to the generator type referred to as generator in the CIM data. b) the delivered BID3 data for the entire year of 2019. Hydro power was not included in the chart, since it represent less than 0.1 ‰ of DK East. c) the presented Energinet (Danish TSO), here misc refers to the groups presented as "Central Power Stations", "Public Power Stations" and "Industrial Autoproducers" [48].

Figure 4.5 may at first glance seem incoherent, but it is important to keep in mind that the ENTSO-E data in a) is a instantaneous value of P_{gen}, whilst b) and c) are mean value from an entire year and therefore can not be expected to correlate 1:1. A detailed comparison is presented in Table 4.1.

Table 4.1: Comparison between WP (off- and onshore for the BID3 data), PV and Thermal/Misc as a share of the energy mix in 2019, for the data from BID3 and Energinet [48]. The top half (above the double line) are for DK West, and the bottom half (below the double line) are for DK East. The Energinet values are recordings and the BID3 values are simulation result based on in data, e.g. grid data, historical load and generation and meteorological data.

BID3	Share (%)	**Energinet**	Share (%)	Difference [-]
WP off- and onshore	57	WP	62	5
PV	3	PV	3	0
Thermal	40	Misc	35	5
WP off- and onshore	49	WP	42	7
PV	4	PV	4	0
Thermal	47	Misc	54	7

Based on the average year values from both BID3 and Energinet, as shown in Figure 4.5. The data is mapped to a fairly close degree in Table 4.1. The largest difference is 7 percentage points for DK East, and that between the category that includes everything except WP and PV.

Lastly, the BID3 data do not contain production nor load for the third zone in Denmark, the large WP area in the Baltic sea: Kriegers Flak. It is assumed that this production is included in the data for DK East, and subsequently the RAW-data has been adjusted so all units that originally, in the ENTSO-E data, was tied to the zone Kriegers Flak, is moved to the zone DK East instead.

4.2 Equivalent Reduced Network

When all of the ENTO-E data is converted into RAW-format, the sheer amount of data, of a grid as large as the combined European one, makes it difficult manage and work with in PSS/E. The idea is to design a model that is less detailed as the original data, but not quite as simplified as the current BID3 copper plate model. Therefore, simplification of the network has to be made. Within PSS/E there is a built-in function, EEQV, to simplify a network to an equivalent (reduced) network. This section will address this function and adjacent work to make this possible.

Before PSS/E can reduce the network with EEQV, the case must be solved to an acceptable degree of mismatch. To ensure that one does not have to solve the entire ENTSO-E network one can solve one area (country) at the time. Since the ENTSO-E data is constructed in such a way that at every national border crossing there is a fictitious bus, a so-called X-bus. All of these X-buses has a common Area code, which means that one can look at the data for a country, e.g. Denmark with the area number 1900, and easily find all of its border buses. This is either done automatically by EEQV, or it could also be done manually by looping through the data and finding what transmission lines are connected to a X-bus (i.e. a border crossing) and at the other bus with area number 1900 is a Danish border bus. To identify what national buses are border buses is very important since PSS/E should only reduce a network within a country, while leaving the interconnections between two countries unchanged.

A couple of simplifications of the Danish grid had to be made due to the fact that PSS/E was not able to find a power flow solution of the original case. Since the total grid of Denmark was divided into two AC-grids, east and west for each SA, the case was also divided into two sub-grids: east and west. In order to solve these cases, the reactive part of the loads was set to zero along with the susceptance of the shunts and AC lines. This simplification was made since the area of interest is active power flow and not voltage levels, voltage regulations nor reactive power flow.

Even after these simplifications, the case could not always be solved. Several buses in the model did not have any equipment on them and were only connected to the grid through one branch or transformer. These buses seemed to be the problem when trying to solve the case and were therefore removed manually. It should be mentioned that these buses would have otherwise been removed by the EEQV function. Some of the buses were connected to the grid via three winding transformers which was replaced by two-winding transformer between the remaining two buses , as can be seen in Figure 4.6.

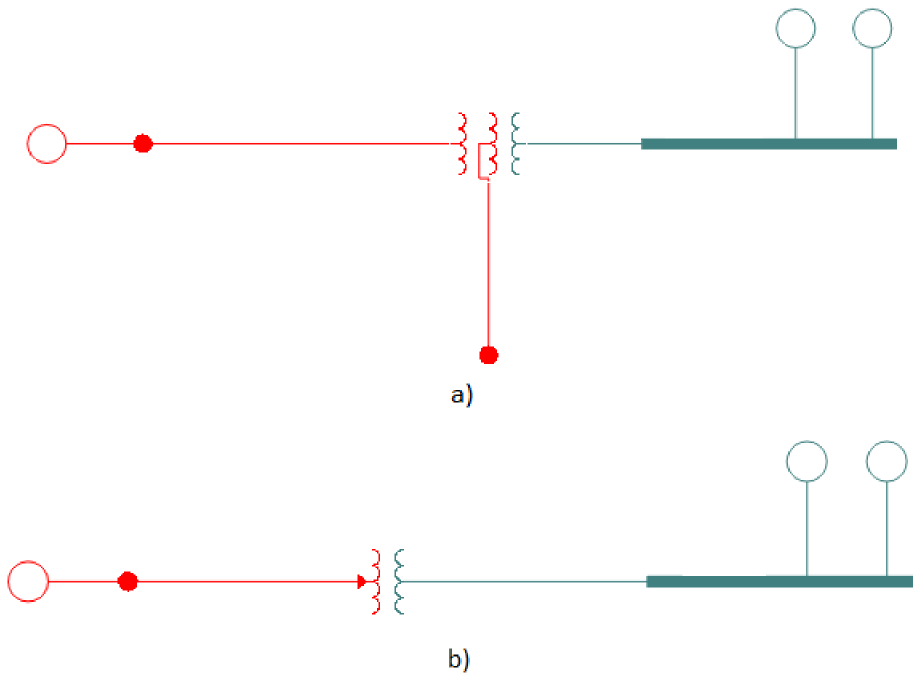

Figure 4.6: Part of network with the three-winding transformer with the third bus not connected with anything else than the transformer itself. In a) the original diagram is shown and b) is after the third bus is deleted and the three-wining transformer is replaced by a two-wining transformer.

What EEQV does is that it utilizes the admittance matrix, here shown in partitioned form

$$\begin{bmatrix} I_{Retained\ nodes} \\ I_{Deleted\ nodes} \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \cdot \begin{bmatrix} V_{Retained\ nodes} \\ V_{Deleted\ nodes} \end{bmatrix} \tag{4.4}$$

where V is the voltage, I the current and Y the admittance, and performs a reduction operation [65]. This is done by rearranging the second row and inserting it into the first row, thereby creating the equation

$$I_{RN} = (Y_1 - Y_2Y_4^{-1}Y_3) \cdot V_{RN} + Y_2Y_4^{-1} \cdot I_{DN} \tag{4.5}$$

which is used to specify equivalent branches, loads and shunts connected to the retained nodes in order to compensate for the changes in by the deletion of nodes.

For the best result one should try and reduce the network in steps. This is something that Siemens stress in their operation manual [65]. It is important to note that there are many more features and options in the EEQV-function than what is mention here, but since the focus of this thesis is on power flow, only those options is described in this report. The process of reducing a network is illustrated in Figure 4.7 can be broken down in the following steps [65]:

- Analyzing the case and identify all the area boundary buses (if applied all the zone boundary buses can also be included in this step).
- Convert all the generators of buses that will be removed from the system to negative loads (if this option is chosen), unless the generator bus has an IDE of 3, i.e. is a swing bus and is therefore exempted, or a IDE of 5, 6 or 7 in which case the bus is excluded from the EEQV-process and will remain unchanged in the equivalent reduced network. There is also a option to have a generation threshold, all generators with a P_{Gen} above this threshold are retained.
- Conduct the admittance matrix reduction operation as stated above and inserting the equivalent branches, loads and shunts. The equivalent components will have the ID "99", which makes it easy to overview the system later on.

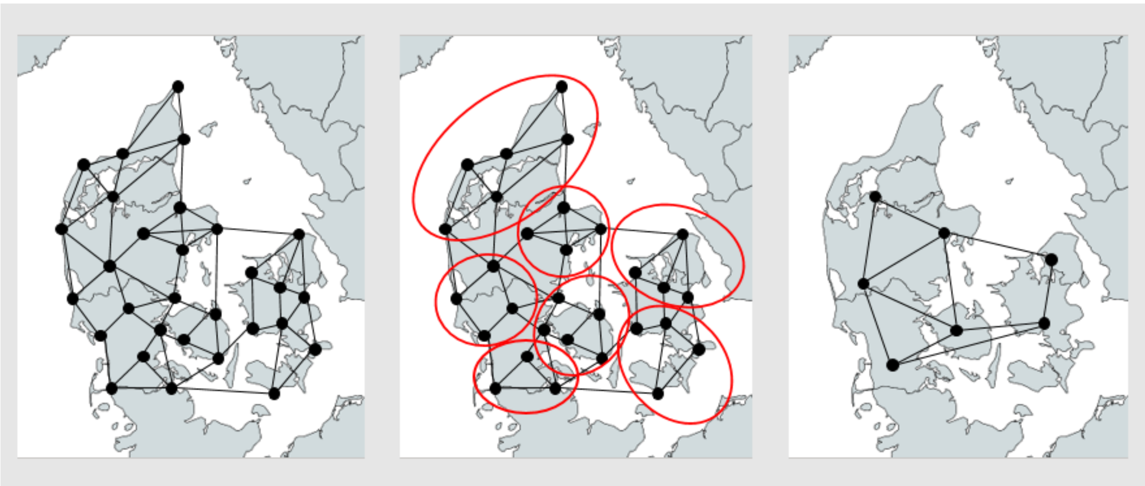

Figure 4.7: Illustration of the process of identifying sub-zones and creating merged buses and equivalent branches equivalent reduced network by the use of EEQV. The node are fictive to illustrate the grid.

As a final note, Siemens urges, in [65], the user to control the output of the swingbus by comparing the generation of the swingbus generator after the EEQV has taken place with the generation before EEQV.

4.3 EEQV options and reduction method

Since there are a number of different options associated with the EEQV-function, e.g. whether or not to keep the generators, two methods for the creation of network models are presented. These two methods are the maximum and minimum limits of how the generators are handled when conducting EEQV. In the first method none of the generators are converted to negative loads or even moved from the bus they are placed at. This means that all buses that had generators connected to them in the original case will be kept. Thereby ensuring that the equivalent network has about the same amount of production as well as load and losses in the system. This method will hereby be referred to as *Method A*. The second method is to not at all consider generator buses when conducting EEQV, resulting in that a lot of the generators will be converted to negative loads. However, generators connected to buses that will be kept, e.g. boundary buses and the swing bus, will not be converted. This network method will hereby be referred to as Method O. These two methods to approach the four load-cases create an interval for the number of buses that the grid could be reduced to: either a maximum number of buses, i.e. an unaltered case (total of 284 buses in Denmark), or a minimum i.e. the fully utilized EEQV (33 buses in Denmark).

The choice was made to solve the different load-cases in the two zones, West and East, separate with method A and O. To get a better perspective of EEQV-function and the different grid representations created by the methods, additional options in different iterations was made. Network Model A-0: The default case and unaltered number of units and buses. Model X-1 (where X is replaced A or O): Empty buses have been manually removed in order for PSS/E to be able to solve the case. Since X-1 does not require the use of EEQV, A-1 and O-1 is the same model. Model X-2: EEQV has been conducted but all PST are kept in the network. This is to keep are more holistic perspective since PST are essential to prevent loop-flows in continental Europe. This was done in two steps, first all of the voltage levels separately and then the whole system. Model X-3: Only border buses and the generator buses that is below the generator threshold level is kept. For Method A this is 100 %, i.e. all of the generators are kept, and 0 % for Method O, i.e. only the swing bus generator is retained. These different options of each model is presented in Table 4.2.

Table 4.2: The number of buses in each zone and in Denmark when applying each model. As seen Method O reduces the network quite drastically, and only the swing bus remains with a generator. Method A still reduces the number of buses in the grid, but here all of the 263 generators are retained.

Network model	DK West	DK East	Total
A-0	144	140	**284**
A-1	134	119	253
A-2	95	69	**164**
A-3	94	58	152
O-1	134	119	253
O-2	23	24	**47**
O-3	21	12	33

As seen in Table 4.2, Model A-2 reduces the number of buses in the grid with over 40 % compared with the default data (A-0). This while all of the generators and PST are kept, i.e. two very important features of a transmission system. Even though method O drastically reduced the amount of buses, it does so at the expense of keeping all of the production units. The decision was therefore made to evaluate the method A and try to improve the methodology by reducing the number of units, while still keep all of the generators. This reasoning behind this was that one should be able to input data from any other load-case after EEQV is performed.

Based on the reasons stated above, an additional method was used to specifically try to improve the results of Method A and focus on the transmission system, this method is called Method B. Method B analyzes the grid and identifies all generators that is connected to a bus with a transformer in turn connected to a higher voltage level. The generators are then moved to the bus with the higher voltage level, on the other side of the transformer, and this is repeated until no more generators can be moved to a higher voltage level via a transformer connection. This process of moving generators is illustrated in Figure 4.8. The B-models will make it easier to merge generation of the same type or, if needed, scale different types of power generation.

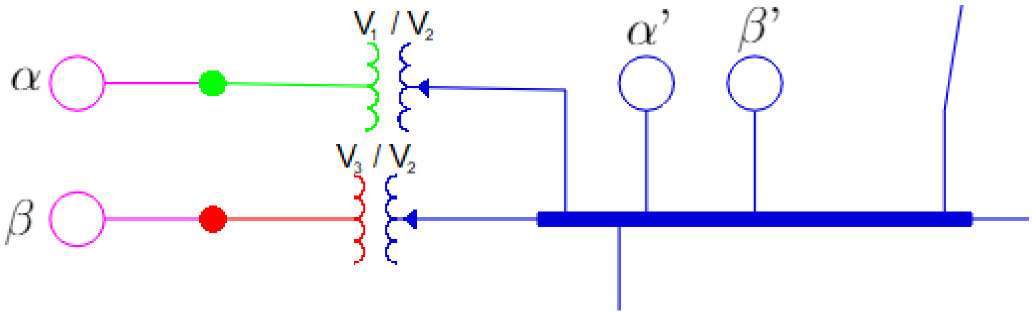

Figure 4.8: Illustration of Method B. Generator α at voltage level V_1 and generator β at voltage level V_3, are here moved to the bus with higher voltage level V_2, thus becoming α' and β'. I.e. generator α and β are removed once they are moved, so α and α' or β and β' never exists at the same time.

The results of the same type of simulation and use of EEQV as used in Method A and O, and presented in Table 4.3.

Table 4.3: The number of buses in the grid when Method B is used. Here the number of buses are reduced even more compared to Method A, but all of the 263 generators are still retained.

Network model	DK West	DK East	Total
B-1	124	110	234
B-2	85	62	**147**
B-3	84	53	137

As seen when comparing Model B-2 to A-2, the number of buses is reduced by 17 but Model B-2 still retain all of the generators and PSTs. If one would like to reduce the system even further, e.g. remove all of the PSTs as well, the number of buses eould be reduced even further, see Model X-3 in Table 4.2 and 4.3. Method B increases the minimum bus voltage of Denmark west from 11.5 kV to 165 kV and of Denmark east from 16 kV to 132 kV, this occurs already at Model B-1.
In Figure 4.9 and 4.10 the models A-0, A-2 and B-2 is presented in a slider diagram for each zone. Note that equivalent branches are drawn when buses, and by extension branches and transformers, are removed in the two figures.

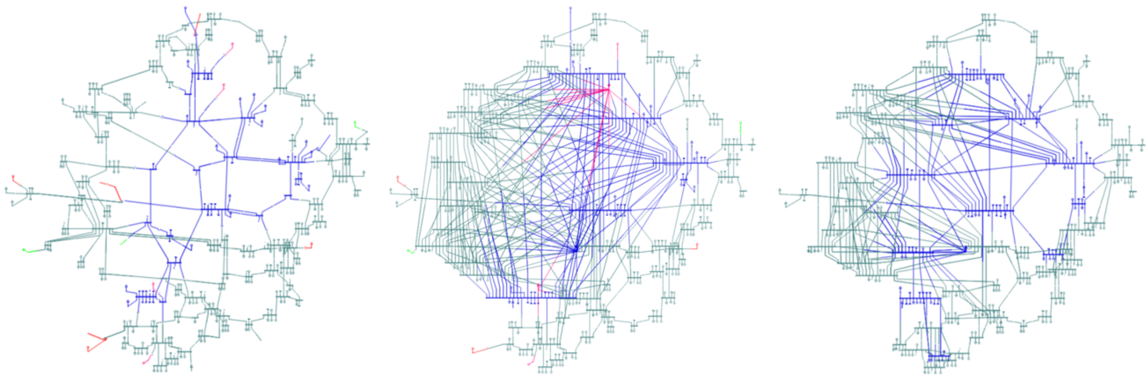

Figure 4.9: Slider diagrams of the Danish transmission system, DK West. From the left: i) unaltered system (Model A-0), ii) Reduced network with equivalent transmission lines also dawn in (Model A-2), iii) Reduced network with generators moved to higher voltage levels, equivalent transmission lines is also drawn in (Model B-2).

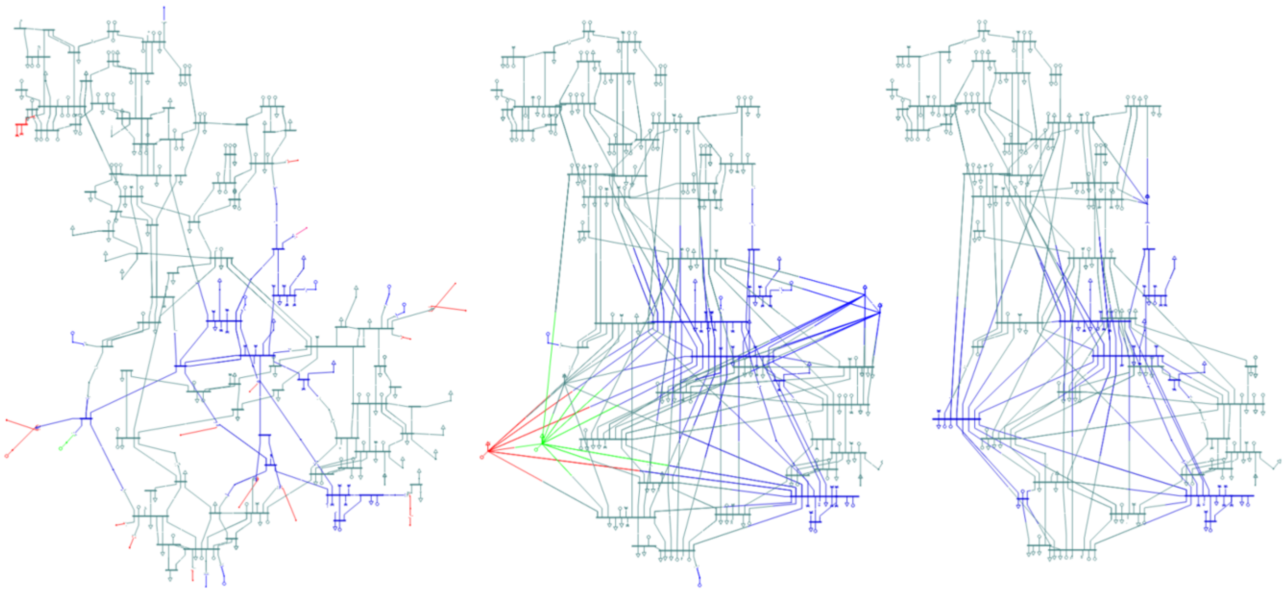

Figure 4.10: Slider diagrams of the Danish transmission system, DK East. From the left: i) unaltered system (Model A-0), ii) Reduced network with equivalent transmission lines also dawn in (Model A-2), iii) Reduced network with generators moved to higher voltage levels, equivalent transmission lines is also drawn in (Model B-2)

4.4 Prediction and recordings of cross-border flow of 2019

No predictions nor model are an exact representation of reality, but in order to evaluate an intended improvement, the original model also need to object of scrutiny. Here follows a comparison of the power flow predicted from BID3 and the actual recordings of ENTSO-E transparency platform [66]. Since this thesis only investigates four key hours, and a prediction for such a small time frame can be dubious at best, the decision was made to make a compression over the entire year of 2019.

By looking at the net power flow between two zones, as presented in Figure 4.11, one can observe the total net power flow difference in a year. It may be worth to keep in mind that BID3 is built to primarily focus on the electric price in different zones and the power flow is heavily influenced by this. Still for most cross-zone transmissions of net power flow, BID3 is quite close to the actual value. As seen in Figure 4.11, there is primarily an inaccuracy in the cross-border transmission between Denmark and Germany.

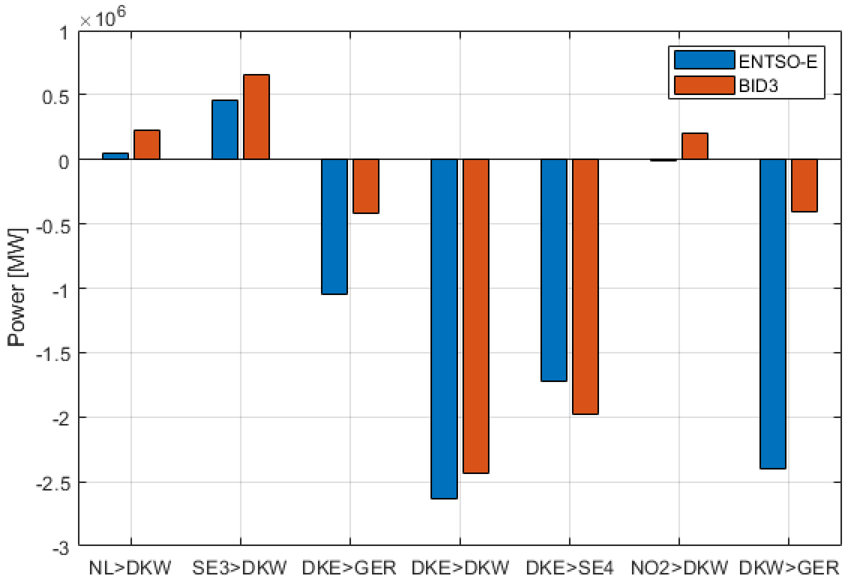

Figure 4.11: Summation of all the power flow in the direction of for example NL to (>) DKW, in the case of the first two bars. Important to note is that the sign of the power flow will effect the sum, i.e this diagram shows the total net flow of the cross-border power flow. The data comes from BID3, and the ENTSO-E data is gathered from Transparency Platform [66]

An complementary method that is useful for comparing the BID3 and ENTSO-E data is to look at the capacity used of the cable, i.e a summation of the absolute value of the transmission. This is presented in Figure 4.12, where one can see that BID3 mostly overestimates the capacity used by cross-border transmission lines. This again may suggest that a more power flow oriented aspect, such as a power flow analysis in PSS/E, could be beneficial to somewhat lessen the weigh of the electricity price in determining the cross-border power flow in BID3. In the case for the power flow from Denmark East to Denmark West the total capacity is only 8 % larger than the ENTSO-E value. The only flow that BID3 predicts a lower figure that actual recorded is Denmark West to Norway, where the BID3 prediction is only 75 % of the ENTSO-E value.

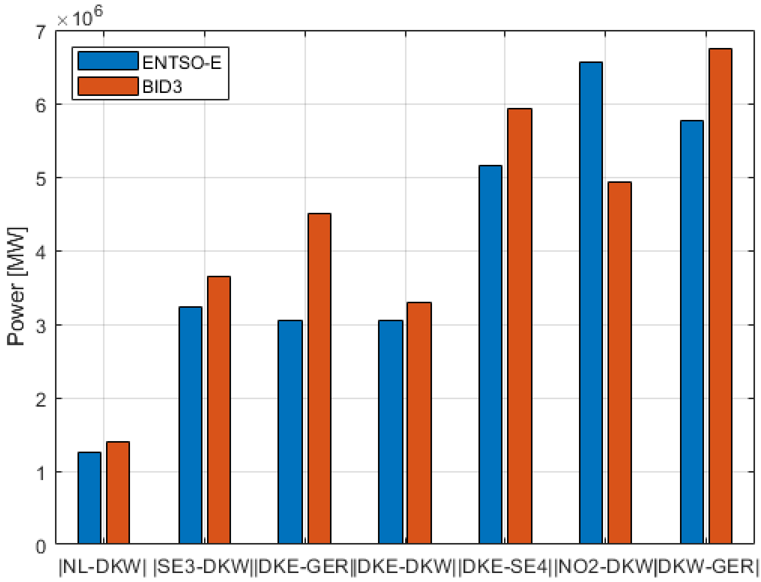

Figure 4.12: Summation of the total power flow, regardless of direction of the power flow, i.e a measurement of the, recorded and predicted, total usage of the transmission lines. The data comes from BID3, and the ENTSO-E data is gathered from the Transparency Platform [66]

It is also worth noticing that for Figure 4.12, the Denmark to Netherlands cable was not in operation until the second half of 2019, and therefore should not be used in valuating the BID3 prediction. Still it is included in order to present the complete data set. Lastly, also worth pointing out is the sometime inconsistency of the ENTSO-E data from Transparency platform. When a few control calculation was carries out to double-check whether the production, load and transmission data coincided, i.e. the sum of them should equal the grid losses, the numbers didn't add up. Sometimes there was an excess of several thousands MW in the grid. Additionally the cross-border data was not always equivalent, when looking at the same hours from two different sets, e.g. to look at the Danish-German numbers from the Denmark-data or from the German-data. These inconsistencies and shortcomings regarding data quality for Transparency platform is nothing new and is in accordance with previous studies [67].

5

Power flow solution results

This chapter contains the results of power flow solutions, how the EEQV function affects the result, how the methods A and B compares to each other as well as to the actual grid in turns of swing bus production, power flow and losses.

5.1 Time required for power flow solution

The time required by PSS/E to conduct a power flow solution for the different models was measured and is presented in Table 5.1. Because of the difference in time between tests, the measuring was conducted 5000 times per model in order to get a good average time. The result indicated that Model B-1 and B-2 could be solved faster than A-1 and A-2. It did not indicate that the equivalent models A-2 and B-2 could be solved faster than the A-1 and B-1 respectively, even though the X-2 models contain fewer buses. The processing power required for the tests were not measured.

Table 5.1: Time required by PSS/E to conduct power flow solution on the different models

Model	A-1 [ms]	A-2 [ms]	B-1 [ms]	B-2 [ms]
DK East	186	196	153	153
DK West	344	343	144	144

5.2 Generation at swing bus

The two following sections will present the power produced at the swing bus. Firstly, the generation from the BID3 input data is compared with the solved case from PSS/E in order to assess the validity of the generation and load distribution of the BID3 data as described in section 4.1.2 as a stable and solvable case. Secondly, the power solutions for the different zones and models are compared before and after the use of EEQV in PSS/E in order to evaluate the network reduction.

5.2.1 Generation before network reduction

Here follows a comparison of the BID3 data, meaning the original production before the case was solved, and the solution of the case from PSS/E. The models used are

Model A-1, i.e. the original case with only the empty buses removed, and later on Model B-1, i.e. moved generators to a higher voltage level and the empty buses are removed. As stated in Section 4.2, a closer inspection of the swing bus net power flow is a fast and easy way to assess the validity of a reduced equivalent network. However, the difference between the BID3 data and the actual solution should not be seen in relation to the amount produced by the swing bus since it is the difference between the entire production for the two cases. The difference will instead be compared to the active power flow of the solved case which is defined as the sum of the active power generated within the area and the active power flow to the area, i.e. the negative load of the X-buses connected to that area.

First, when using Model A-1, in Table 5.2 one can observe that there are low to moderate differences between the predicted generation at the swing bus and the solved case. HLHP sticks out with a higher difference than the other load-cases in MW but similar to LLLP in percentage of active power flow. The case HLLP has a very small difference as percentage of active power flow, while LLHP is slightly higher although not close to the higher two.

Table 5.2: Swing bus generator production with BID3 data compared to solved case for Denmark (both zones), using Model A-1, i.e. the original case, and only the empty buses are removed. The difference is between BID3 input and Solved case.

Case	HLHP	HLLP	LLHP	LLLP
BID3 input [MW]	804.1	318	276.9	105.2
Solved case [MW]	865.3	316.5	267.7	128.4
Difference [MW]	-61.2	1.5	9.2	-23.2
Active power flow [MW]	8556.3	5236.4	6271.8	3505.1
Difference as percentage of active power flow [%]	-0.72	0.03	0.15	-0.66

When the BID3 input power is larger then that of the solved case there is a slightly larger difference with Model B-1 compared to A-1, as seen in Table 5.2 and 5.3 respectively. The opposite is also true, that when the BID3 input power is smaller than that of the solved case, the difference is a slightly smaller for Model B-1 compared to A-1. This is because of the lower active power production of Model B-1. For LLLP and HLLP the difference between the BID3 inputted generation and the actual solution from PSS/E changes very little between Model A-1 and B-1. The reason that there is a larger production for Model B-1 is because the swing bus is not the same as for Model A-1 and there is now more than one generator at the swing bus. Method B caused the generator at the swing bus of Model A to be moved and the bus was removed.

Table 5.3: Swing bus generator production with BID3 data compared to solved case for Denmark (both zones), using the Model B-1, i.e. moved generators to higher voltage level and the empty buses are removed. The difference is between BID3 input and Solved case.

Case	HLHP	HLLP	LLHP	LLLP
BID3 input [MW]	1100	423.8	387.2	146.8
Solved case [MW]	1155.4	422	374.1	169.3
Difference [MW]	-55.4	1.8	13.1	-22.5
Active power flow [MW]	8550.5	5186.1	6267.8	3504.5
Difference as percentage of active power flow [%]	-0.65	0.03	0.21	-0.64

Overall, regardless of model, the generation at the swing bus from the BID3 input and the solved case is below 1 % of the active power flow.

5.2.2 Generation after network reduction

Since all the generators are kept with Method A and Method B, no loads are being canceled out with negative load from equivalent generators by EEQV. This results in that the equivalent networks, using models A-2 and B-2, should have essentially the same amount of active power production as the solved cases using models A-1 and B-1. This means that the difference in active power production can be used to indicate whether or not EEQV-generated grid is an accurate equivalent network with the specific load-case.

From both Table 5.4 and 5.5 it is obvious that there is a very small difference in the swing bus active power generation between the Model X-1, where are only the empty unused buses are deleted, and the Model X-2 where the network has been reduced by the EEQV-function and the PST has been kept. The most stressed control variable by Siemens [65] for a successful reduced equivalent network is to compare the swing bus output before and after EEQV. As seen the the bottom line of both Table 5.4 and 5.5, there is a very small difference.

Table 5.4: Swing bus active power production for Equivalent networks with models A-1 and A-2

Case	HLHP [MW]	HLLP [MW]	LLHP [MW]	LLLP [MW]
A-1 DK W Solved	488.6	145.1	126.7	50.1
A-2 DK W Solved	488.5	145.1	126.6	50
Difference DK W	0.1	0	0.1	0.1
A-1 DK E Solved	376.7	171.4	141	78.3
A-2 DK E Solved	377.3	171.9	141.6	78.7
Difference DK E	-0.6	-0.5	-0.6	-0.4
Tot abs Difference	0.7	0.5	0.7	0.5

Table 5.5: Swing bus active power production for Equivalent networks with models B-1 and B-2

Case	HLHP [MW]	HLLP [MW]	LLHP [MW]	LLLP [MW]
B-1 DK W Solved	742.2	233.8	221.9	87.3
B-2 DK W Solved	742.1	233.7	221.8	87.2
Difference DK W	0.1	0.1	0.1	0.1
B-1 DK E Solved	413.2	188.2	152.2	82
B-2 DK E Solved	413.2	188.3	152.2	82
Difference	0	-0.1	0	0
Tot abs Difference	0.1	0.2	0.1	0.1

Note that Method B, where the generators are moved to a higher voltage level, in addition to have even fewer nodes than Method A, the difference in swing bus power output is also smaller.

5.3 Losses

The losses for Model A-1 and B-1 are presented in MW and also as a percentage of both the consumption and active power flow in the system in Table 5.6 and 5.7. This is because losses are often presented as a percentage of consumption and probably an average over a larger time span, e.g. a year. So, in order to evaluate how realistic the losses of the models are it would be preferable to do the same. However, since this report only examines four different extreme hours, there is an imbalance between the production and consumption for the different load-cases resulting in that the cases with high load consequently has lower losses as percentage of the consumption. On the other hand, as the active power flow is always higher than the consumption, the losses as a percentage of the active power flow will be smaller. Therefore, the average of the losses as a percentage of the consumption could give a value suited for comparison to what the load should be while the losses as a percentage of the active power flow is better suited to compare the losses between the different load-cases.

Table 5.6: Power flow solution results for the entirety of Denmark with Model A-1. Losses for each zone can be found in Appendix A.

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	62.2	29.8	47.3	39.4
Consumption [MW]	5700.1	4803.6	2989.9	2433.7
Losses as percentage of consumption [%]	1.09	0.62	1.58	1.62
Losses as percentage of active power flow [%]	0.73	0.57	0.75	1.12

Table 5.7: Power flow solution results for the entirety of Denmark with Model B-1. Losses for each zone can be found in Appendix A.

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	56.4	29.5	43.2	38.8
Consumption [MW]	5700.1	4803.6	2989.9	2433.7
Losses as percentage of consumption [%]	0.99	0.61	1.44	1.59
Losses as percentage of active power flow [%]	0.66	0.57	0.69	1.11

Both Model A-1 and B-1 have fairly low losses. Even so, Model A-1 consistently generates marginally higher losses, but they are still lower than expected. Based on the fact that the vast majority of the branches and buses of the ENTSO-E data are 165 kV or higher the losses should at least be between 1-2.5 % [48], [49], [50], . The average value of the load as percentage of consumption is 1.22 % and 1.16 % for models A-1 and B-1 respectively, which is inside of the 1-2.5 % range. This in turn makes the lower losses with Model B-1 fairly reasonable since even more power production is transferred to a high voltage level, i.e. lower transmission losses.

LLLP has significantly higher losses in percentage of power flow than the other three load-cases. This is a because of the combination of medium amount of losses in MW and very low active power flow. For LLLP, Denmark west has considerably lower losses than Denmark east at 6.6 MW and 32.8 MW respectively, despite having relatively similar amounts of power flow at 1 926.4 MW and 1 578.8 MW respectively. The losses as percentage of active power flow is presented in Figure 5.1 and as can be seen, the losses of Denmark west are the lowest for the load-case LLLP while in Denmark east it has the highest losses in MW and by far the highest in percentage of power flow.

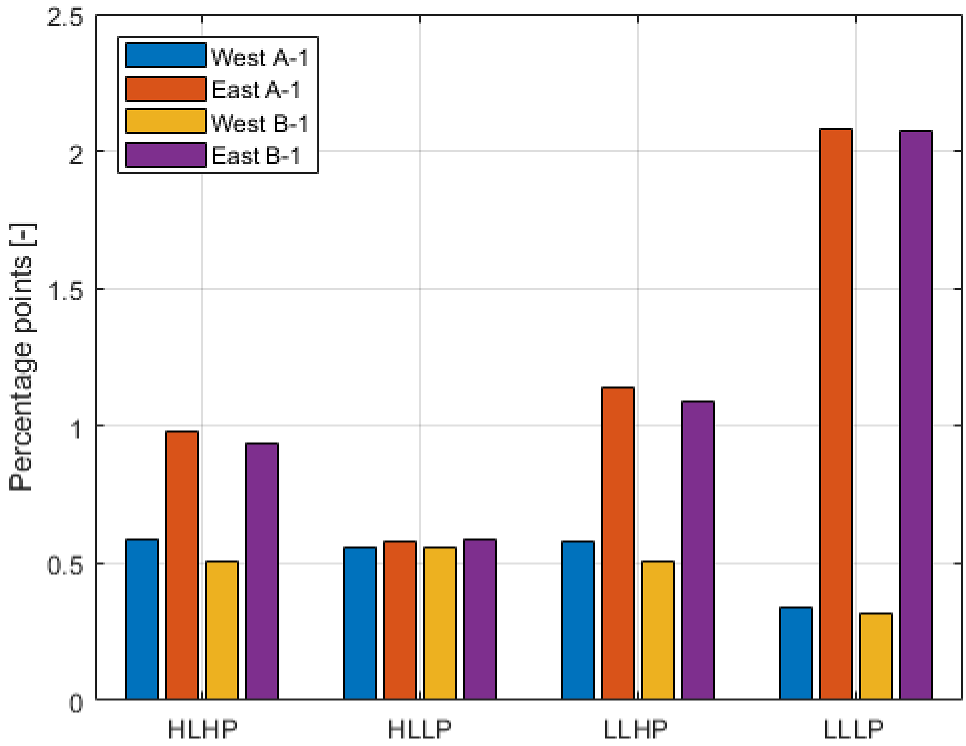

Figure 5.1: Bar diagram illustrating the power losses as percentage of the total active power flow in each zone with model A-1 and B-1. This can also be read in Table 5.6 and 5.7.

The change in the amount of losses is arguably the most important variable to study. This is because the production and consumption can simply be exchanged for other values. When conducting EEQV, some of the losses becomes load or part of a G-shunt while some is simply deleted, which causes the production to be lowered. The losses for the Model A-2 and B-2 are presented in Table 5.8 and Table 5.9 respectively.

Table 5.8: Power flow solution results for the entirety of Denmark with Model A-2

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	60.9	29.1	47	39.2
Losses as percentage of consumption [%]	1.07	0.61	1.57	1.61
Losses as percentage of active power flow [%]	0.71	0.56	0.75	1.12

Table 5.9: Power flow solution results for the entirety of Denmark with Model B-2

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	55.1	29.3	42.6	38.5
Losses as percentage of consumption [%]	0.97	0.61	1.42	1.58
Losses as percentage of active power flow [%]	0.64	0.56	0.68	1.10

When comparing the losses, as percentage of consumption and as percentage of active power flow, between A-1 and A-2 in Table 5.6 and 5.8 respectively, only very small differences can be seen. The largest difference is 0.02 percentage points for load-case HLHP. The rest of the load-cases have no or smaller differences in losses when using model A-1 compared to A-2. When examining the difference between model B-1 and B-2 in Table 5.7 and 5.9, it is also very minor differences. As with the A-models, the largest difference is 0.02 percentage points when comparing losses as percentage of consumption and as percentage of active power flow. This suggests that the EEQV only marginally affects the losses in the network.

5.4 Power flow and interconnection of Denmark

When looking at the connection to the X-buses specifically, for Model A-1, one finds that LLLP has 13.1 MW losses on the connections between X-buses and the buses belonging to Denmark east. This is not only the highest amount for the different load-cases in MW, but more than double that of the second highest, being HLHP. Out of these connections the Denmark east to Denmark west connection contributes with the highest amount of losses at 7.10 MW. What can also be seen is that Denmark east receives 323.6 MW from Germany which is then transported via two buses in Denmark east to the connection between Denmark east and Denmark west, causing around 6.3 MW in losses.

5.5 Data irregularities

In the CIM-data provided by ENTSO-E there are a few irregularities that in various degrees affects the final output. One of theses irregularities are the fact that several three-winding transformers have extremely uneven and high reactance on one or more windings. After several attempts to adjust and work around this, they had to be replaced with two-winding transformer, as illustrated in Figure 4.6. To get a sense of how high some reactants are, one of the three-winding transformers have a reactance of 0.12, 0.0035 and 8.4 p.u.

A factor well worth pointing out is that a part of the distribution grid data in the CIM-data was already reduced/made equivalent. It is possible that a regional DSO had its data made equivalent, before sent to the Danish TSO, and then to ENTSO-E. Since it is unknown how good the equivalent system is, nor how large system it represent. It is impossible to know how much it affects the final results of this thesis. Furthermore it is worth underlining that the majority of the losses in a national electric network stems from the distribution system. This could be one reason to explain why the simulated PSS/E system, both before the EEQV and after, has such low losses. It could not be the only source for the lack off losses, but may be one contributing factor.

The BID3-data is specifically for the year 2019, based on data from primarily ENTSO-E Transparency platform, while the CIM-data from ENTSO-E is based on the grid, but is suppose to represent the grid in the year 2025. Although not optimal, since electric infrastructure is very time consuming to contract it should not make large difference in the end results. On the subject, difference in BID3 and ENTSO-E data, as it may be worth repeating that even thought the CIM-data is for the year 2025, there is not a single solar plant in the system, rather it is merged in the miscellanies group "generators". Also it is regrettable that the CIM-data do not differentiate between on- and offshore WP, thus limiting the full usage and extent of the BID3 data, which are more finely meshed in regards to power plant categorization.

6
Discussion

This chapter provides discussion of the models created and the results of the power flow solutions. Furthermore, how the results could be utilized and what impact the results of this thesis could have on future studies as well as the ethics of the power system sector and on the environment.

6.1 Models

The equivalent branches that are created by EEQV in order to compensate for branches and transformers removed when a "middle-bus" is deleted so that power can still flow between two buses that are kept. EEQV may therefore actually increase the number of branches. However, this does not necessarily mean that a model is more complex since the power flow between two buses should not change except for that it might not have to flow through a "middle-bus".

It is unclear why PSS/E seems to be able to conduct a power flow solution remarkably faster for models B-1 and B-2 compared to models A-1 and A-2 even though the number of buses was not reduced nearly as much by moving the generators to a higher voltage level as by EEQV. A consequence of moving the generators is that fewer transformer are needed, i.e. fewer calculations, thus possibly enabling PSS/E to produce a solution faster. What sticks out is the fact that it took PSS/E 10 ms longer to solve A-2 than A-1, the reason could be that EEQV required to many equivalent branches, thereby making the model more complicated. However, the tests were simple and the processing power was not measured so it is difficult to draw any conclusion from these results alone. Furthermore, if production could be centralized on a fewer number of buses then EEQV would have a larger impact on the grid and not requiring to create as many equivalent branches which might reduce the time required to conduct a power flow solution.

6.2 Swing bus generation

The generation data from BID3 distributed at each generator according to the method stated in section 4.1.2 seems to result in a power generation at the swing bus that is very, or moderately, close to the power calculated by PSS/E in the power flow solution. From these few, although extreme, cases the result from Table 5.2 and 5.3 suggests that the generation distribution method in section 4.1.2 and BID3 data in the ENTSO-E based grid results in a stable and solvable grid model.

Furthermore, based on the result of the generation at the swing bus before and after the EEQV-function is used, both Method A and B yields extremely small active power differences. The smaller total power difference of Method B compared to Method A, suggest that this may be preferable, or at least that the EEQV function is more viable for Method B. This method might even be more accurate if it was worked on even further. For example if a revised method B enabled the possibility to represent a national grid with only 165 and 400 kV units or even solely with the 400 kV units, thus reducing the number of buses and units even further.

The extremely small difference in power output at the swing buses, together with the drastic reduction of buses that is possible with Model A-2 and B-2, suggest that the ENTSO-E and BID3 data together with the EEQV-function in PSS/E, could be viable option for at least representing neighboring transmission systems, when simulation a national transmission system.

6.3 Load-cases

From both the duration curve and the graph of the load and production in chronological order in section 4.1.1, one can observe that the load and the power production is highly volatile. Based on this, as well as wanting to test the BID3 data for more extreme load and production condition, the four cases HLHP, HLLP, LLHP and LLLP was chosen. Since each case took a fair amount of time both to insert the correct BID3-data into the RAW-file, and later on performing each Method in PSS/E, these cases posed quite enough work. If there was more time, it would have been very interesting to investigate a few more moderate hours to see what results that would generate. Based on the current data from the various methods for each of the four load-cases, a more common load and production case could probably also be simulated and calculated fairly accurate. At last, this is only speculations, and actual tests would have been interesting.

6.4 System losses

The losses are relatively small for Model A-1, especially for the load-case HLLP, but the average over the four hours are within the range 1-2.5 %. This is however largely because of the high losses of case LLLP, where the X-bus connections to Denmark east causes a large amount of the losses. This makes it harder to establish whether the losses are reasonable or not since the flow causing these losses is not only inside of Denmark. In addition, this thesis only considers four extreme hours and looking at the losses as a percentage of the consumption over the entire year would probably provide a more accurate view of whether the losses are reasonable.

For Model B-1, the losses for Denmark as a whole are less than that of Model A-1 for all four load-cases. This is because some of the moved generators were connected to buses which only had a single connection; the transformer that previously connected the now removed generator. By moving these generators, one also removes the losses that would occur if power would have been transmitted over these transformers. Furthermore, it is worth to keep in mind that power transmitted via a line with a higher voltage level, have lower losses compared to a comparable transmission line on a lower voltage level. However, it was not investigated if this had actually contributed to the lower losses since it could also be the case that this resulted in more power flowing through the transformers that the generators were moved over. The smaller losses makes Method B less accurate in regard to system losses, particularly at lower voltage levels, than Method A since the move of generators were not compensated for in any way. On the other hand, the main area of interest is to model the power in the grid and its flow, i.e. moving the generators could be a beneficial trade off in this regard. If one would like to better represent the grid losses, i.e. to include the transformer losses of the removed transformer with Method B, additional impedance loads could be inserted into the grid as a compensation. This is however not done in this report to due time restraint and the scope of this thesis.

6.5 Use of results and future work

The results and models of this thesis could be used when simulating an area in Europe, e.g. northern Germany. In this case it would be very processing power intensive to use the unaltered entirety of the ENTSO-E network data and historical demand, load, and cross-border flow for not only Germany itself, but also neighboring countries. Instead, one could divide Germany into several zones, from north to south, and represent both the southern zones as well as the neighboring countries to the northern zone as equivalent reduced networks. The northern zone itself would probably be kept in its original state, but on the other hand it could also be reduced to some extent, e.g. with Model B-2, while the rest could in varying degree be reduced even further.

Those cases, when representing a neighboring zone or area as a equivalent reduced network, could perhaps be used to improve BID3. By introducing grid constraints within a zone or area, one might perhaps shift the center of gravity in BID3 away from electricity price somewhat, thus representing the real world even more accurate. On the other hand this is a trade off and the perfect compromise between accurate representation and efficient processing power utilization is outside the scope of this thesis.

Firstly, future work should consider testing more hours for Denmark and of course model the rest of the European transmission system. The modeling of Europe could be exemplified by the design a test case such as the one described for northern Germany. Secondly it would be interesting if a future thesis would undertake to try to further develop and refine the models of reducing the network. This thesis only came as far as Method B, although it still manages to reduce the number of nodes from 284 to 147 (B-2), or 137 B-3 if PSTs would not have to be included. With more time this numbers could probably become even lower, without a significant loss of information and properties of the grid. Lastly, it would be fascinating to in greater detail explore the generator threshold in EEQV and how a reasonable limit could be calculated.

6.6 Ethics and environmental impact

In order to make the environmental goals of the EU [68] a reality the transmission systems of Europe has to change with the shift in electricity generation, e.g. as in Germany [23]. Since a transmission system is immensely complex, not to mention 42 interconnected ones, it is important to test and simulate various scenarios. BID3 could be a key tool for many TSO, DSO and power producers to better be able to meet the challenges of tomorrow.

Nothing is morally strictly *good* or *evil*, RES is no exception. Drawbacks from RES ranges from EMI caused by inverts in PV [69], [70], to the sound pollution [71] and changes in the landscape from onshore WP and its impact on humans and animals [72], [73]. For new transmission lines to reinforce the transmission systems of Europe there are several non-technical challenges such as a fierce local public opposition and drawn-out court cases [74]. Some TSO have chosen to in a larger extent use underground cables to reduce the number of court appeals [74], [75], and some governments, e.g. Sweden's, have publicly stated that they aim to reduce the individual's right to appeal a decision to a higher court [76]. This in turn begs the ethical question if a individual should give up some of her democratic freedoms, such as the right to appeal, in a state governed by law in order to compensate for previous governments inaction.

Regardless the potential consequences, by improving simulation software and methods one can strive for an utilitarian and environmental friendly electrification of the world of tomorrow.

6.7 Division of labor

Throughout this thesis there has been a fair and equal division of labor. Initially Patrik read up more about the Challenges of Europe while Josef focused on the governing body and the European energy market. Thereafter both did a lot of work in order to get the CIM-data into RAW format, and lastly Patrik focused on integrating the BID3-data into the RAW-file while Josef performed virtually all the PSS/E simulations. None the less the work process and division of labor have been functional and lessens the consequences of pandemic related restrictions, as well as only having access to one PSS/E v35 license.

7
Conclusion

As a methodology the process of scaling the production and load from the ENTSO-E-data with the BID3-data and thereafter performing EEQV in PSS/E seems valid. Based on the comparison of the number of buses in the grid, the production at the swing bus and the load and system losses, a reduced equivalent network as a representation of the original grid is a viable option for introduce constrain into an otherwise copper plate model. However, what this thesis fails to show is to what degree this methodology should be performed. The three methods, A, B and O, all produce solvable cases, but with varying level of detail. Method O is arguably to close to a copper plate model and do not represent the total production nor load of a load case, still the method probably demands less processing power.

When deciding whether Method A or B is the most useful, the accuracy of losses has to be weighed against seemingly faster power flow solution, focus on the transmission grid and the number of buses. Model A-2 is based on the original model, minus empty buses, and should produce the most accurate power flow simulation in terms of losses, but has 17 more buses than Model B-2. B-2 could also be considered to be the model better representing the transmission grid as well as enabling power flow solution in less time. Both model A-2 and B-2 should produce sufficient results, therefore if the difference in number of buses is shown to have a sufficient impact on performance, then B-2 should be used. Furthermore, B-2 could most likely be developed even further through compensation for losses of the deleted transformers and the removal of low voltage generators, and lastly by the adjustment of generator threshold.

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A

Appendix 1

A.1 Generation at swing bus before network reduction - Zone

Table A.1: Swing bus generator production with BID3 data compared to solved case for Denmark west

Case	HLHP	HLLP	LLHP	LLLP
BID3 [MW]	474.4	169	170.2	70.4
Solved case [MW]	488.6	145.1	126.7	50.1
Difference [MW]	-14.2	23.9	43.5	20.3
Difference as percentage of a active power flow [%]	-0.25	0.71	1.01	1.05

Table A.2: Swing bus generator production with BID3 data compared to solved case for Denmark east

Case	HLHP	HLLP	LLHP	LLLP
BID3 [MW]	329.7	149	106.7	34.8
Solved case [MW]	376.7	171.4	141	78.3
Difference [MW]	-47	-22.4	-34.3	-43.5
Difference as percentage of a active power flow [%]	-1.59	-1.19	-1.76	-2.76

Table A.3: Swing bus generator production with BID3 data compared to solved case for Denmark west

Case	HLHP	HLLP	LLHP	LLLP
BID3 [MW]	732.8	257.8	268.4	108
Solved case [MW]	742.2	233.8	221.9	87.3
Difference [MW]	-9.4	24	46.5	20.7
Difference as percentage of a active power flow [%]	-0.17	0.72	1.08	1.07

Table A.4: Swing bus generator production with BID3 data compared to solved case for Denmark east

Case	HLHP	HLLP	LLHP	LLLP
BID3 [MW]	367.2	166	118.8	38.8
Solved case [MW]	413.2	188.2	152.2	82
Difference [MW]	-46	-22.2	-33.4	-43.2
Difference as percentage of a active power flow [%]	-1.56	-1.21	-1.71	-2.74

A.2 Grid losses per zone

Table A.5: Power flow solution results Denmark west, A-1

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	33.3	18.8	25	6.6
Consumption [MW]	3360	2976.5	1839.4	1488.8
Active power flow [MW]	5602.3	3347.3	4320.4	1926.4
Losses as percentage of consumption [%]	0.99	0.63	1.36	0.44
Losses as percentage of active power flow [%]	0.59	0.56	0.58	0.34

Table A.6: Power flow solution results Denmark east, A-1

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	28.9	11	22.3	32.8
Consumption [MW]	2340.1	1828.1	1150.5	945.9
Active power flow [MW]	2954	1889.1	1951.4	1578.8
Losses as percentage of consumption [%]	1.23	0.60	1.94	3.47
Losses as percentage of active power flow [%]	0.98	0.58	1.14	2.08

Table A.7: Power flow solution results Denmark west, B-1

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	28.5	18.6	21.9	6.2
Consumption [MW]	3360	2975.5	1839.4	1487.8
Active power flow [MW]	5597.5	3347.1	4317.3	1926
Losses as percentage of consumption [%]	0.85	0.63	1.19	0.42
Losses as percentage of active power flow [%]	0.51	0.56	0.51	0.32

Table A.8: Power flow solution results Denmark east, B-1

Case	HLHP	HLLP	LLHP	LLLP
Active power losses [MW]	27.9	10.9	21.3	32.6
Consumption [MW]	2340.1	1828.1	1150.5	945.9
Active power flow [MW]	2953	1839	1950.5	1578.5
Losses as percentage of consumption [%]	1.19	0.60	1.85	3.45
Losses as percentage of active power flow [%]	0.94	0.59	1.09	2.07

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