


ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

MASTER EN INGENIERÍA INDUSTRIAL

# ANALYSIS OF POWER-NETWORK PARAMETERS FOR DATA VALIDATION

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Madrid

Julio 2018

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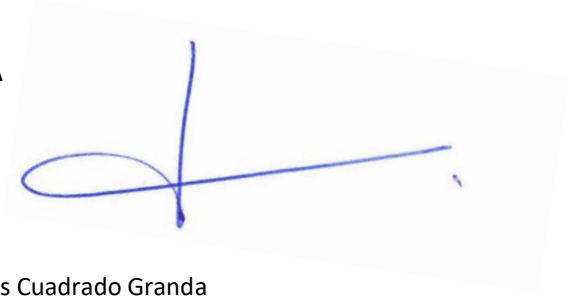
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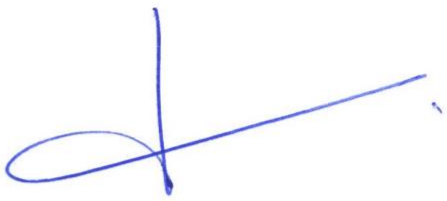


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ANALYSIS OF POWER-NETWORK PARAMETERS FOR DATA VALIDATION

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Fdo.: Andrés Ramos Galán Fecha: 17/07/2018



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Julio 2018

ANALISIS DE PARAMETROS DE RED DE TRANSPORTE PARA VALIDACION DE DATOS

**Autor: Cuadrado Granda, Luis.**
Director: Ramos, Andrés; Espejo, Rafael.
Entidad Colaboradora: IIT – Universidad Pontificia Comillas.

# RESUMEN DEL PROYECTO

Alrededor del mundo y en Europa en particular, esta habiendo un cambio de paradigma energético. El modelo tradicional de generación centralizada y transporte de electricidad esta cambiando a uno con mas presencia de generación distribuida, con flujos bidireccionales convirtiéndose en la norma en vez de la excepción. La UE tiene un objetivo de penetración renovable del 35% en 2030 [1], en línea con estas perspectivas. Los perfiles de demanda están cambiando también, con el incremento de la electrificación de sectores como el transporte. Esto esta llevando a una fuerte inversión en investigación y desarrollo de nuevas redes, empezando por la descripción de las redes existentes en el máximo detalle posible.

Este proyecto busca analizar detenidamente la información publicada por ENTSO-E, un consorcio europeo de 46 TSOs, e identificar posibles relaciones y patrones entre parámetros. Una serie de reglas de validación serán desarrolladas para verificar cualquier otro conjunto de datos, que pueden ser usados en una gran variedad de aplicaciones como puede ser el desarrollo de redes sintéticas. Existen iniciativas privadas como OpenGridMap [2] para las cuales esta metodología de validación puede ser interesante de cara a intentar validar las contribuciones ofrecidas por la comunidad.

La información disponible sobre las redes eléctricas puede caracterizarse por la falta de datos sobre alguno de los parámetros que describen las misma, información errónea o discordancia entre diversos orígenes de la información. El objetivo es verificar la información usada y extraer una metodología de validación. Donde la información falte, posiblemente asignar valores, donde sea errónea, detectar dichos errores y cuando provenga de fuentes diversas, buscar coherencia. El valor añadido surge del análisis no sólo estadístico de la información, cómo se podría realizar con técnicas de minado de datos, si no que lo complementa con un análisis desde el punto de vista de ingeniería eléctrica. Este estudio se centra en el análisis de los siguientes parámetros: resistencia, reactancia, susceptancia capacitiva y capacidad de transporte, buscando proponer límites por país y voltaje.

**Modelo de línea de transporte**

Para caracterizar los parámetros de línea, un modelo usado típicamente es el modelo equivalente en Π. Esta simplificación, representa los componentes longitudinales y

transversales de las líneas de transporte. Resistencia y reactancia aparecen en serie mientras que susceptancia capacitiva y conductancia aparecen derivadas a tierra.

**Resistencia (R)**

El calculo teórico de la resistencia se puede observar en la Ecuación 1 e ilustra como la resistencia depende de la línea y la sección del conductor.

$$R = \rho \frac{L}{S} \ [\Omega]$$

**Ecuación 1: Resistencia de conductor**

Donde $\rho$ es la resistividad del conductor a 20º C, en $\Omega \cdot mm^2/m$, $L$ es la longitud del conductor en metros y $S$ es la sección del conductor en $mm^2$. A la resistencia también le afecta la temperatura y el efecto pelicular.

**Reactancia (X)**

La reactancia de la línea causa una caída de tensión a lo largo de la línea como consecuencia de la fuerza electromotriz que aparece cuando una corriente alterna sinusoidal fluye por el conductor. La ecuación que relaciona la frecuencia y la reactancia inductiva se puede observar en la Ecuación 2.

$$X = 2\pi f L_K \ [\Omega]$$

**Ecuación 2: Formulación de reactancia inductiva**

Donde $f$ es la frecuencia de la corriente alterna a través del conductor en Hercios y $L_K$[H/km] es un parámetro que depende de la geometría de la línea y la naturaleza del medio en el que se haya la línea.

**Susceptancia Capacitiva**

Las líneas de transporte trifásicas siempre se componen de mas de un conductor. Como entre los conductores hay una diferencia de potencial y están aislados entre ellos, actúan como un condensador. Este parámetro tiene una importancia no despreciable, ya que está ligado a la generación y almacenamiento de energía reactiva en la línea. Su formulación se puede observar en la Ecuación 3.

$$B = C_K \cdot \omega = C_K \cdot 2 \cdot \pi \cdot f \ [S]$$

**Ecuación 3: Formulación de susceptancia capacitiva**

Donde $C_K$ es la formulación de la capacidad.

**Análisis de los datos**

**Resistencia**

En redes de transporte, los voltajes de trabajo son principalmente 220 kV y 400 kV. Otros voltajes se han podido observar en algunos países y en otras tecnologías de transporte como HVDC.

De cara a intentar cumplir los objetivos del proyecto, los parámetros se comparan considerando voltaje y localización, en particular, el país al que pertenecen.

Una característica que se puede extraer de los datos es el tamaño relativo de las resistencias máximas de los países. A 400 kV, que suele incluir las líneas de mayor

distancia, Alemania, España y Francia tienen los valores mas altos, lo cual esta en línea con que estos países sean los de mayor extensión en Europa.

En cuanto a una posible estimación de la resistencia con la capacidad de transporte de la línea, puede ser interesante identificar relaciones en un histograma, observable en la Figura 1.

Los cuatro clusters principales han sido destacados y la información sobre resistencia de esos cuatro clusters descrita en la Tabla 1.

| | 276-576 | 576-1176 | 1176-1550 | 1550-2076 | 2076-2376 | 2376-2676 | 2676-3426 |
|---|---|---|---|---|---|---|---|
| R Max | 15,405 | 7,590 | 9,499 | 11,360 | 3,632 | 4,154 | 3,261 |
| R Min | 0,008 | 0,007 | 0,008 | 0,002 | 0,037 | 0,002 | 0,010 |
| R Average | 1,861 | 1,178 | 1,604 | 1,335 | 1,092 | 0,794 | 0,762 |
| R St. Dev | 2,150 | 1,484 | 1,540 | 1,208 | 0,937 | 0,644 | 0,677 |
| N. of Lines | 315 | 196 | 638 | 1060 | 47 | 451 | 59 |

**Tabla 1: Resistance statistics for different thermal rating clusters for lines at 400 kV**

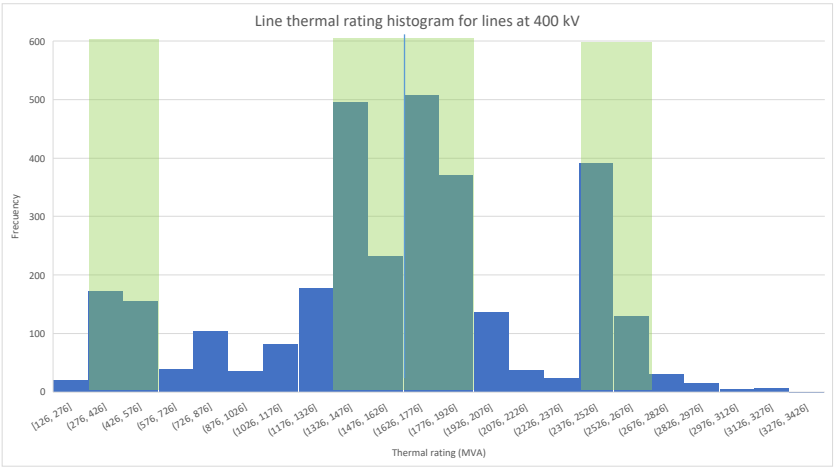



**Figura 1: Histograma de Thermal Rating de líneas a 400 kV**

Se puede observar una clara tendencia de resistencia decreciente. La Figura 2 ilustra la relación entre la resistencia de la línea y su longitud. Se puede apreciar que hay cuatro tipos de línea a 220 kV en Francia.

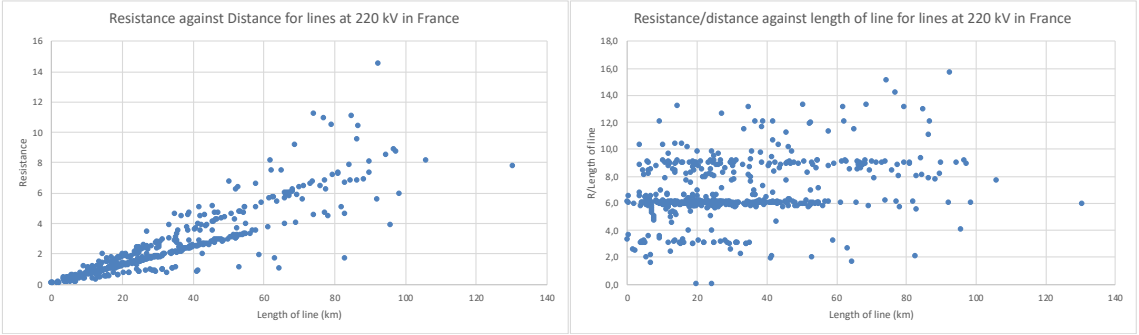



**Figura 2: Resumen de relaciones de resistencia contra distancia en Francia a 220 kV**

## Reactancia

El tamaño relativo de las reactancias entre países es interesante al haber una variabilidad menor que la resistencia. A diferencia de los datos de resistencia, no hay línea que tengan

una reactancia de valor nulo. La relación entre reactancia y longitud de línea es claramente lineal, cuando esta información esta disponible.

La relación que es interesante destacar es el de X/R, como se puede observar en la Figura 3. Países con un índice de desarrollo mayor tienen, en general, ratios X/R mayores. Esto se debe probablemente a que el numero de conductores por circuito es mayor en general es dichos países, como se puede demostrar con cálculos teóricos. El resumen de dichos cálculos se puede observar en la Tabla 2.

| | X/R | | | | |
|---|---|---|---|---|---|
| | Single Circuit | | Double Circuit | | |
| | 1 | 2 | 3 | 4 | Global Average |
| **Simplex** | 100% | 100% | 98% | 102% | **1,00x** |
| **Duplex** | 143% | 143% | 139% | 147% | **1,43x** |
| **Triplex** | 269% | 269% | 264% | 275% | **2,69x** |

**Tabla 2: Resultados del cálculo teórico de X/R**

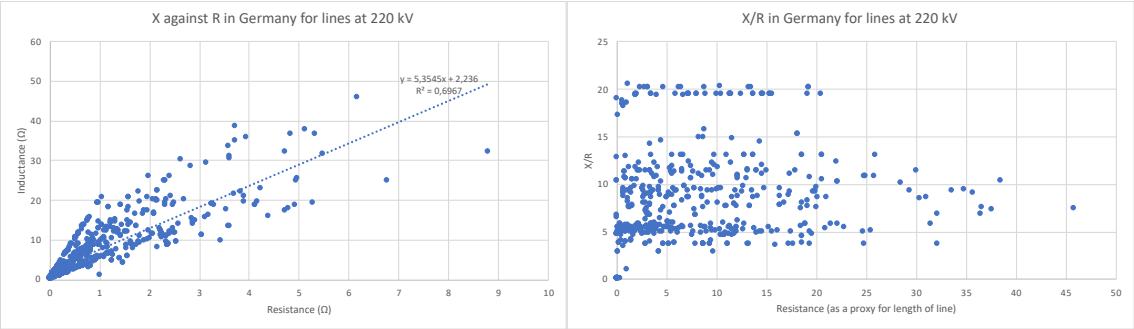



**Figura 3: Relaciones X/R de línea a 220 kV en Alemania**

## Susceptancia Capacitiva

Del mismo modo que con resistencia y reactancia, la relación entre longitud de línea y susceptancia capacitiva es claramente lineal, cuando esta información esta disponible. En cuanto a su relación con resistencia, en la Figura 4 se puede observar como una ratio de susceptancia capacitiva por unidad de longitud en Francia está ligado a otro ratio de resistencia por unidad de longitud. Esto se debe probablemente a los diferentes tipos estándares de líneas usados con algún conductor en particular.

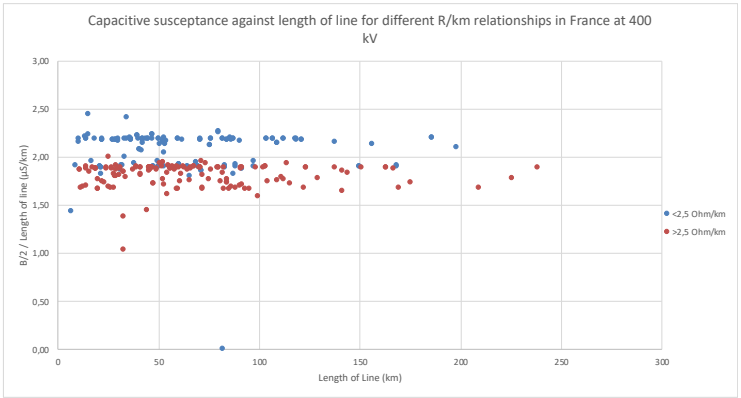



**Figura 4: Susceptancia capacitiva por unidad de longitud contra R/km en Francia en líneas a 400 kV.**

Por último, es interesante verificar, donde hay información para ello, la relación entre la longitud real de una línea y la longitud esférica en línea recta entre sus extremos. En

teoría, la longitud real debe ser igual o más larga que la longitud en línea recta. La Figura 5 confirma esto.

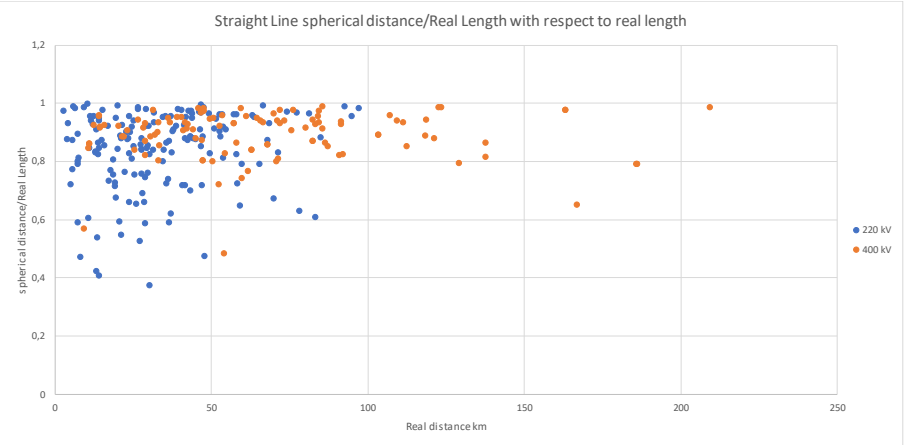



**Figura 5: Relationship between spherical and quoted distance between nodes**

## Metodología de Validación

La metodología de árbol de decisión ha sido escogida para verificar todos los valores. Para empezar, labores máximos y mínimos se contrastan para todos los países y voltajes, siendo valores fuera de este rango considerados erróneos o a ser justificados individualmente. A continuación, se verifica caer dentro del 2% al 98% percentiles empíricos por país y voltaje, siendo cualquier valor fuera de este rango estudiado, pero no considerado descartable inmediatamente. Finalmente, la relaciones como X/R y los parámetros por unidad de distancia, donde estén disponibles, deberán ser contrastados. Las relaciones de parámetros tienen el beneficio añadido de no estar afectados por la longitud de la línea, por lo que se pueden usar cuando dicha longitud no este disponible. Por último, un contraste similar se ha de hacer en los datos de transformadores y bancos de condensadores, si hay información sobre ellos.

## Referencias

[1] Schiermeier, Q. (2018). European Union moves to strengthen renewable-energy goals. [online] Nature.com. Available at: https://www.nature.com/articles/d41586-018-00879-9

[2] Opengridmap.com. (2018). OpenGridMap. [online] Available at: http://opengridmap.com

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# PROJECT SUMMARY

Around the world, and in Europe in particular, the energy paradigm is shifting. The traditional model of centralised generation and transport of electricity is changing to one more heavily based on distributed generation, with bidirectional flows across lines becoming the norm. The EU has a renewable penetration objective of 35% by 2030 [1], in line with this trend. The demand profiles are also changing with the electrification of many sectors such as transportation. This is leading to a large investment in research and development of new grids, starting by the description of the existing network in as much detail as possible.

This project aims to closely analyse the information published by ENTSO-E, a European consortium of 46 TSO's, and identify possible patterns and relations between parameters within the data. A set of validation criteria will also be developed to verify any other data set, to be used in a diversity of applications such as the development of synthetic power grids. There are some private initiatives such as OpenGridMap [2] for which this validation methodology could be very interesting in an effort to validate possible contributions by the community.

Current electrical models have characteristics which can be missing, erroneous and from diverse sources. The objective is to check the data used and to extract a validation methodology. Where data is missing, possibly assign values, where data is erroneous, detect said errors and where data is from diverse sources, look for coherence. The added value stems from the viewing of data not as random data, but as an engineer with electrical criteria. The methodology will be based on looking at resistance, reactance, capacitive susceptance and thermal rating and establishing limits on a per country and voltage level basis.

**Transmission Line Model**

To characterise the line parameters, a common model used is the nominal Π – circuit. This simplification represents the longitudinal and transversal characteristics of power lines. Resistance and Reactance of the line are represented by a resistance and reactance in series and conductance and capacity are represented by a capacitor and a resistance derived to earth.

**Resistance (R)**

The theoretical calculation of the resistance is described in Equation 4 and illustrates how the resistance depends on the length and the cross-section of the conductor.

$$R = \rho \frac{L}{S} \ [\Omega]$$

**Equation 4: Conductor Resistance**

Where $\rho$ is the resistivity of the conductor material at 20º C, in $\Omega \cdot mm^2/m$, $L$ is the conductor length in metres, and $S$ is the conductor cross-sectional area in $mm^2$.
Resistance is also affected by the temperature and the skin effect.

**Reactance (X)**

The reactance in a line causes a drop in voltage across said line and is a consequence of the electromotive force that appears when sinusoidal alternating current flows through a conductor. The simple equation that relates frequency to the calculation of the inductive reactance can be observed in Equation 5.

$$X = 2\pi f L_K \ [\Omega]$$

**Equation 5: Inductive reactance formulation**

Where $f$ is the frequency of the alternating current through the conductor in Hertz and $L_K$[H/km] is a parameter that depends on the geometry of the line and the nature of the medium through which it is travelling.

**Capacitive Susceptance (B)**

Transmission lines are always composed of more than one conductor, one for each phase. As the different conductors of a three-phase power line are constantly at different voltages and insulated between each other, they act as a capacitor. This parameter has quite a high importance as it is linked to reactive power generation and accumulation. Its formulation can be observed in Equation 6.

$$B = C_K \cdot \omega = C_K \cdot 2 \cdot \pi \cdot f \ [S]$$

**Equation 6: Capacitive Susceptance formulation**

Where $C_K$ is the capacity formulation.

**Analysis of data**

**Resistance**

In transmission networks, mainly two voltage levels are used; 220 kV and 400 kV. Other voltage levels may be found in different countries or transmission technologies, i.e. HVDC.
With a view to fulfilling the objectives of this project, line parameters are always compared considering voltage level and location, that is, based on the country they belong to.
A feature that can be extracted from the data is the relative size of the maximum resistances within different countries. At 400 kV, which usually entails the lines that cover the longest distances, Germany, Spain and France have the highest values, which is in line with them being the countries with the largest extensions in Europe.

Regarding the possible estimation of resistance from thermal rating it might be interesting to identify possible relations with a histogram, as can be observed in Figure 6.

If four clusters are made from the histogram, the resulting resistance information from those four main clusters and three intermediate clusters and their variability is summarized in Table 3. The main clusters have been highlighted.

| | 276-576 | 576-1176 | 1176-1550 | 1550-2076 | 2076-2376 | 2376-2676 | 2676-3426 |
|---|---|---|---|---|---|---|---|
| R Max | 15,405 | 7,590 | 9,499 | 11,360 | 3,632 | 4,154 | 3,261 |
| R Min | 0,008 | 0,007 | 0,008 | 0,002 | 0,037 | 0,002 | 0,010 |
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**Table 3: Resistance statistics for different thermal rating clusters for lines at 400 kV**

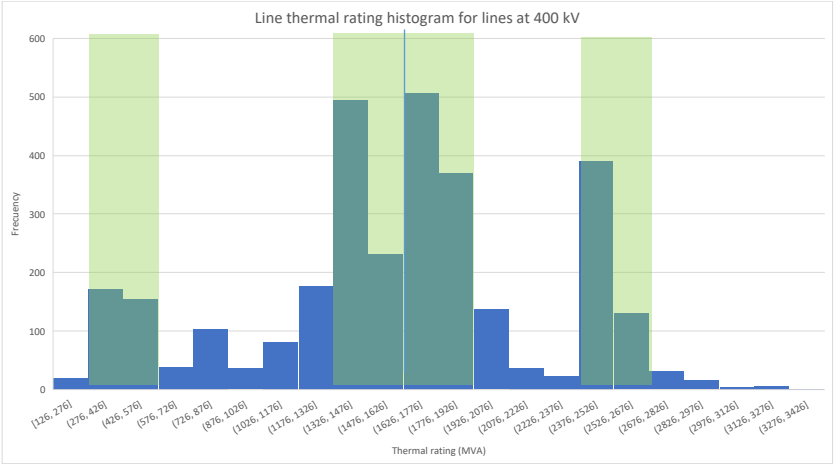



**Figure 6: Thermal rating Histogram for lines at 400 kV.**

A clear trend of decreasing resistance with increasing thermal rating becomes apparent in these clusters.

Figure 7 illustrates the relationship between line resistance and their length. It is very clear that there are four main types of lines at 220 kV in France.

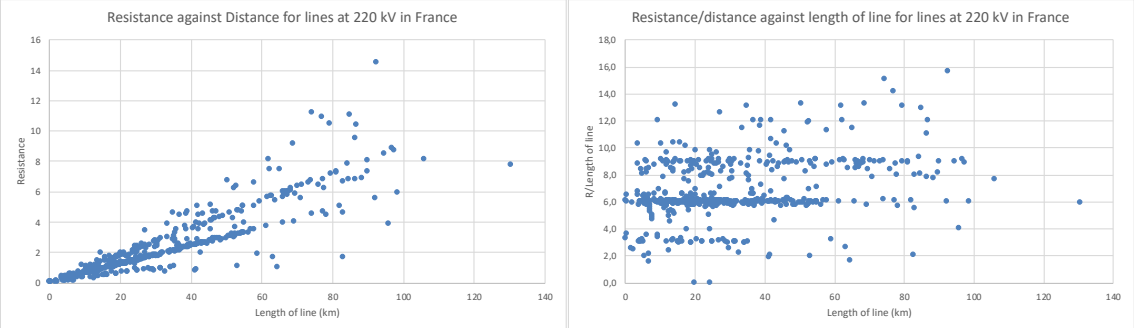



**Figure 7: Relation summary between R and distance in lines at 220 kV in France**

### Reactance

The relative size of the reactances between countries is interesting to mention as there is much less variability than with resistance. Unlike in the resistance data, there are no lines that have a zero value for reactance. The relationship between inductance and distance, where available, is very clearly linear.

A ratio of components that is interesting to note is the X/R ratio, as can be observed in Figure 8. Countries with a higher development have higher X/R ratios in general, this is probably due to the number of conductors per circuit being larger in such countries, as can be shown in the theoretical calculation. Results from these calculations are shown in Table 4.

| | X/R | | | | |
|---|---|---|---|---|---|
| | Single Circuit | | Double Circuit | | |
| | 1 | 2 | 3 | 4 | Global Average |
| **Simplex** | 100% | 100% | 98% | 102% | **1,00x** |
| **Duplex** | 143% | 143% | 139% | 147% | **1,43x** |
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**Table 4: X/R theoretical calculation results**

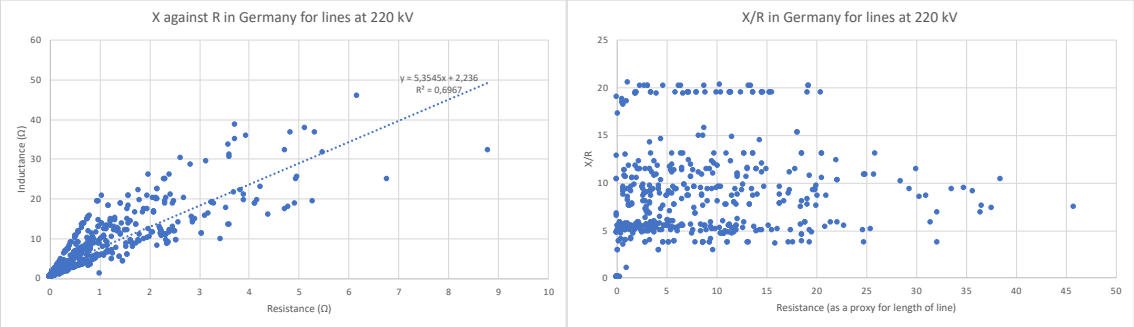



**Figure 8: X/R relationships in Germany at 220 kV**

## Capacitive Susceptance

Similarly to resistance and reactance, the relationship between line distance and capacitive susceptance is clearly linear, where the data is available. Regarding capacitive susceptance and its link to resistance, in Figure 9 it can be observed how a certain ratio of capacitive susceptance and distance is linked to resistance and distance in France. This is probably due to different standard configurations of cables being constructed with specific cable types.

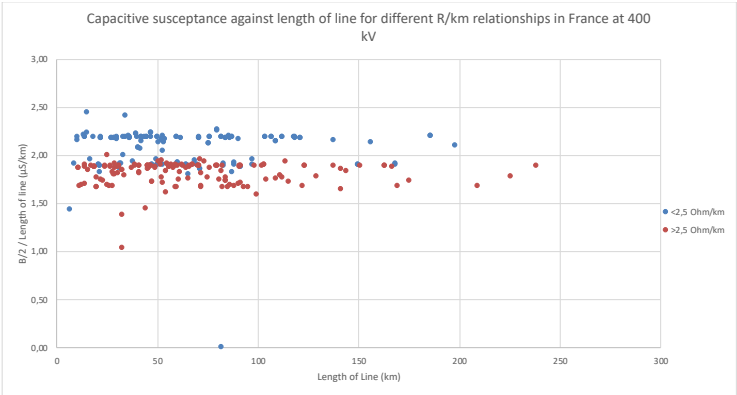



**Figure 9: Capacitive susceptance against length of line for different R/km relationships in France at 400 kV**

As a final note, it is interesting to verify, wherever possible, the relationship between the quoted length of a line and the straight-line distance between the geolocation of the nodes it joins. In theory, the quoted distance must be equal or longer than the straight-line distance as it is impossible to have a shorter distance than the theoretical straight line that

joins the two extremes. Figure 10 shows this and confirms the assumption of quoted lines being under the spherical straight-line distance.

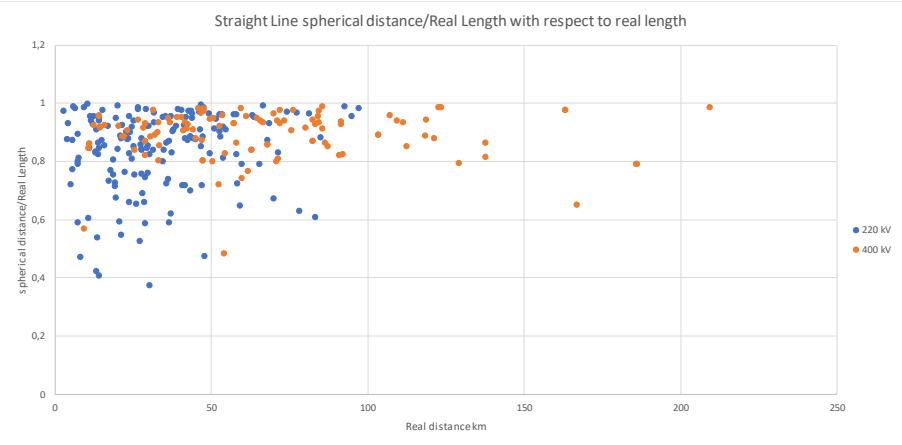



**Figure 10: Relationship between spherical and quoted distance between nodes**

## Validation Methodology

Overall, a decision tree methodology used to verify all values. To start, maximum and minimum values per country are verified for all electrical parameters, being any values outside this range strongly advised to be revised. Furthermore, a 2% to 98% empirical percentiles per country should be verified, scrutinised but accepted if no error in units has been made. Finally, relationships such as X/R and parameters per unit distance, where available, should be verified. These ratios have the benefit of ignoring the length component when it is not available. Finally, a similar analysis should be made for transformer and shunt data, if it is available.

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[1] Schiermeier, Q. (2018). European Union moves to strengthen renewable-energy goals. [online] Nature.com. Available at: https://www.nature.com/articles/d41586-018-00879-9

[2] Opengridmap.com. (2018). OpenGridMap. [online] Available at: http://opengridmap.com

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# 1. Introduction

Around the world, and in Europe in particular, the energy paradigm is shifting. The traditional model of centralised generation and transport of electricity is changing to one more heavily based on distributed generation, with bidirectional flows across lines becoming the norm. The EU has a renewable penetration objective of 35% by 2030 [1], in line with this trend. The demand profiles are also changing with the electrification of many sectors such as transportation. This is leading to a large investment in research and development of new grids, starting by the description of the existing network in as much detail as possible.

## 1.1. Prior Initiatives

Current electrical models have characteristics which can be missing, erroneous and from diverse sources. There are some private initiatives such as OpenGridMap [2], which strive to generate an open source database of electrical networks, with little focus on the verification of the contributions made. ENTSO-E itself, a European consortium of 46 TSO's, by publishing the information, looks to generate an open data set, yet it does not provide a validation methodology or any colour around the values it publishes.

## 1.2. Motivation

A set of validation criteria is a very useful tool to be developed in this area. By doing so, any database of lines to be analysed can be quickly compared and verified with the data provided by ENTSO-E, therefore adding credibility to any study. The diversity of applications to which this could also help are immense, such as the development of synthetic power grids. Other private initiatives such as OpenGridMap [2] could benefit from this validation methodology, in an effort to validate possible contributions by the community.

## 1.3. Project Objectives

This project aims to closely analyse the information published by ENTSO-E and identify possible patterns and relations between parameters within the data. The objective is to check the data used and to extract a validation methodology. Where data is missing, possibly assign values, where data is erroneous, detect said errors and where data is from diverse sources, look for coherence. The added value stems from the viewing of data not as random data, but as an engineer with electrical criteria.

## 1.4. Methodology

The methodology will be based on looking at resistance, reactance, capacitive susceptance and thermal rating and establishing limits on a per country and voltage level basis. This contribution starts by describing the different transmission-line models and analysing the data in Section 2, followed by describing the models and the data analysed regarding transformers and shunts in Section 3, focusing on the resistance, reactance, capacitive susceptance and thermal rating of lines. Following a discussion of the data analysed in Section 4, the validation criteria is described in Section 5 followed by a brief conclusion in Section 6.

## 1.5. Resources

The main tool used to do the data analysis is Microsoft Excel, and the data sets on which the analysis will be based are, mainly, the ENTSO-E 2016 ten-year network development plan (TYNDP), as well as the 2014 edition. On top of these, RTE, the French TSO, as well as the Danish and Belgian TSO's publish data individually that will be used. The complete list of references used is included in Section 8.

# 2. Transmission Lines

The transmission power network is formed by a series of high voltage lines that transmit the electricity from the power plants to the consumption centres before it is distributed at lower voltages. In this paper, the voltages understood to be in transmission space are those above 220 kV. In Europe, some transmission lines work in DC, although there are only a small number of lines like this and most of them are under construction [3]. This paper focuses on AC lines. DC lines are usually used to connect asynchronous systems or systems working at different frequencies and transmit power at very high voltages or long distances. At these levels, reactive power uses a high percentage of the capacity of the line in AC systems, reducing their power carrying capacity. The skin effect also causes the conductor section to have to be quite large, in comparison with a DC line which is able to utilise the complete section of the conductors [4].

## 2.1. Transmission Line Models

### 2.1.1. Π - equivalent circuit

To characterise the line parameters, a common model used is the nominal Π – circuit. This simplification, which can be observed in Figure 1 represents the longitudinal and transversal characteristics of power lines. Resistance and Reactance of the line are represented by a resistance and reactance in series and conductance and capacity are represented by a capacitor and a resistance derived to earth, as can be observed in Figure 1. This simplification is generally accepted for lines under 200 km. Above this threshold, the line parameters are considered to need to be distributed, resulting in a much more complex equivalent circuit and requiring a more detailed characterization. The information presented in this chapter about power lines is extracted from the Overhead Power Lines textbook by Kiessling et al. [4]

For lines under 200km, it can be approximated that the current derivations to ground are negligible ($I_{c1}$ and $I_{c2}$), due to which, when analysing the line information provided by ENTSO-E, this parameter has not been considered as it is not provided.

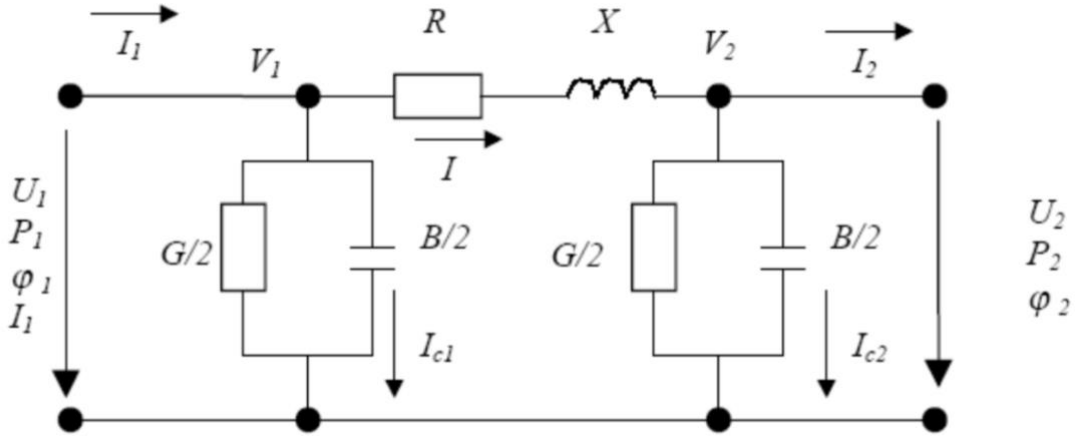



**Figure 1: Equivalent pi circuit. Source: Mujal, R. (2002). Calculo de líneas y redes eléctricas. 1st ed. Edicions UPC.**

### 2.1.2. T - equivalent circuit

As well as the nominal Π – circuit, another simplification often used is that which concentrates the conductance and capacity of the line into a single leg half way across the line, splitting the resistance and the reactance into two. This can be observed in Figure 2. The individual parameters of this and the Π – circuit will be described in the following section.

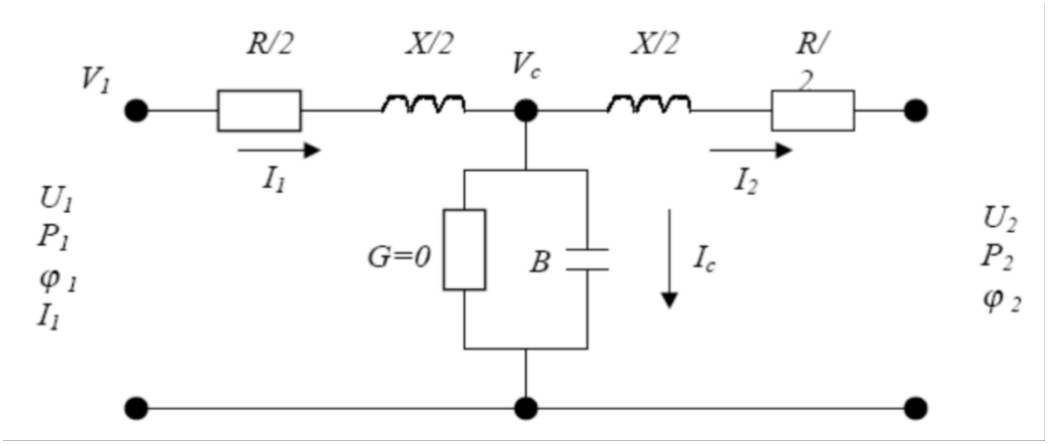



**Figure 2: Equivalent T circuit. Source: Mujal, R. (2002). Calculo de líneas y redes eléctricas. 1st ed. Edicions UPC.**

## 2.2. Transmission line Parameters

In both the previous circuits, the same parameters where used in different configurations. All these parameters can be measured once the line is constructed but there are empirical relations that allow one to estimate to a high degree of certainty the values of the resistance, reactance and capacitance.

### 2.2.1. Resistance (R)

The resistance that exists in a transmission line is the largest cause of losses of energy in the system. The largest consequence of this resistance is the losses caused by the Joule effect through heat.

The effective resistance is calculated as:

$$R_{effective} = \frac{P(Power\ loss\ through\ conductor)}{I^2}\ [\Omega]$$

**Equation 1: Effective Resistance**

Where $P$ is the power lost in Watts and $I$ is the effective current through the conductor in Amps.

With respect to the theoretical calculation of the resistance, Equation 2 illustrates how the resistance depends on the length and the cross-section of the conductor.

$$R = \rho\frac{L}{S}\ [\Omega]$$

**Equation 2: Conductor Resistance**

Where $\rho$ is the resistivity of the conductor material at 20º C, in $\Omega \cdot mm^2/m$, $L$ is the conductor length in metres, and $S$ is the conductor cross-sectional area in $mm^2$.

In general, the main materials used in transmission lines are aluminium and copper, with iron also being used but intended as a structural material due to the poor behaviour under fatigue of aluminium.

This shows a proportional relation with length and an inverse proportionality with cross section, but the reality of lines is that they are usually composed of several conductors intertwined into a plait-like shape for structural integrity [3]. This, on top of the change in resistivity with temperature, as well as the pellicular effect inherent to AC conductors results in a very different resistance. These adjustments, though, are relatively small and vary with frequency and the seasons, which hover around 50 Hz always in the European case, with very small variations, and the average temperature of their respective countries, respectively. Equation 3 and Equation 4 illustrate the causes of temperature and the skin effect on resistivity and resistance.

$$\rho_e = \rho_{20ºC} + \rho_{20ºC} \cdot \alpha(T - 20º)\ [\Omega \cdot \frac{mm^2}{m}]$$

**Equation 3: Resistivity dependence on temperature variations**

$$R'_{TAC} = R'_{20DC} \cdot [1 + \alpha(T - 20)] \cdot (1 + ys)\ [\Omega]$$

**Equation 4: Resistance dependence on pellicular effect**

Where $\alpha$ is the thermal coefficient of resistivity and $ys$ is a pellicular-effect correction coefficient.

### 2.2.2. Reactance (X)

The reactance in a line causes a drop in voltage across said line and is a consequence of the electromotive force that appears when sinusoidal alternating current flows through a conductor. The simple equation that relates frequency to the calculation of the inductive reactance can be observed in Equation 5.

$$X = 2\pi f L_K\ [\Omega]$$

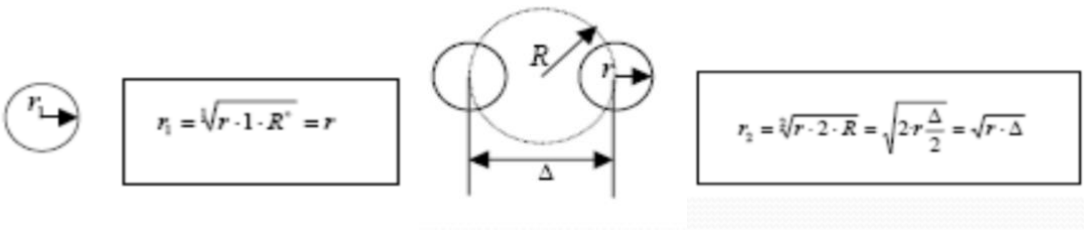
**Equation 5: Inductive reactance formulation**

Where $f$ is the frequency of the alternating current through the conductor in Hertz and $L_K$[H/km] is a parameter that depends on the geometry of the line and the nature of the medium though which it is travelling. In three phase lines with complete composition, the value of the reactance has been approximated to be:

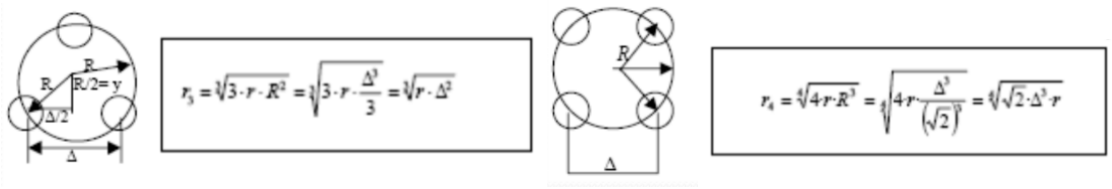
$$L_K = \left[\frac{\mu}{2 \cdot n} + 4{,}6 \cdot \log\left(\frac{D_e}{r_e}\right)\right] \cdot 10^{-4}\left[\frac{H}{Km}\right]$$

**Equation 6: Reactance formulation**

where $\mu$ is the magnetic permeability of the conductor, taking a value of 1 for copper, aluminium and alloys, and 200 for galvanised steel, $n$ is the number of sub conductors and $D_e$ and $r_e$ are factors dependant on the geometry of the lines. $D_e$ is the mean geometric distance between phases and $r_e$ is the equivalent radius formed by the different conductors of each phase. Figure 3 and Figure 4 illustrate these relationships.




**For one conductor.** **For two conductors**




**For three conductors** **For four conductors**

**Figure 3: Illustration of calculation of equivalent radius. Source: Mujal, R. (2002). Calculo de líneas y redes eléctricas. 1st ed. Edicions UPC.**

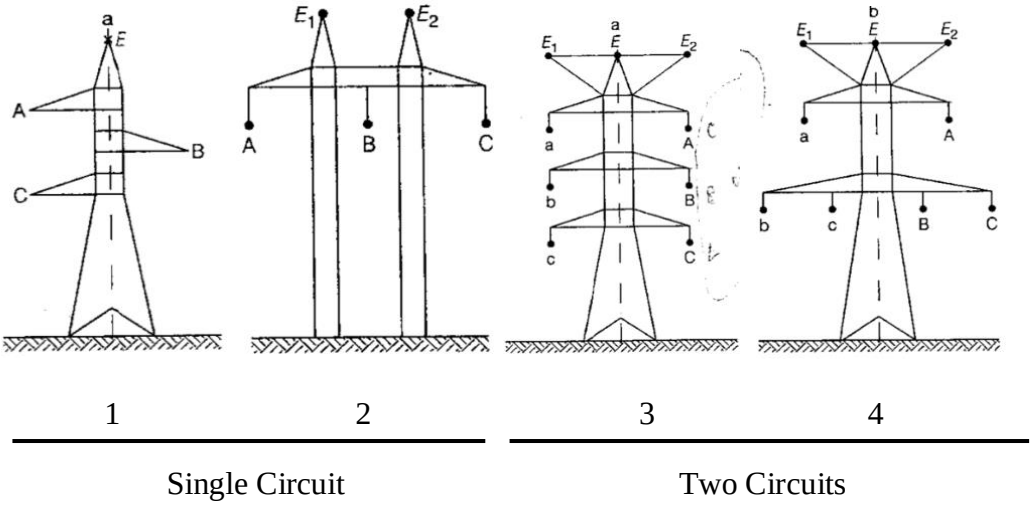



**Figure 4: Illustration of different geometric distances between phases. Source: Mujal, R. (2002). Calculo de líneas y redes eléctricas. 1st ed. Edicions UPC.**

From this relation it can be deduced that, assuming similar if not equal materials for the cables, the only factors that will affect the reactance of a line will be geometric and configuration ones. This relation will not be linear as with resistance, but lines are usually constructed in a series of standard configurations by each TSO, meaning there should be an appreciable clustering of reactance's within countries. A few example calculations of the difference in mean geometric distances can be seen below.

**Single Circuit – 1**, with distances of 8m horizontally from A to B, and 4,5m vertically from A to B and from B to C.

$$D_e = \sqrt[3]{D_{AC} * D_{AB} * D_{BC}} = \sqrt[3]{9 * 9{,}17 * 9{,}17} = 9{,}11\ m$$

**Single Circuit – 2,** with horizontal distances of 7,3m from A to B and B to C.

$$D_e = \sqrt[3]{D_{AC} * D_{AB} * D_{BC}} = \sqrt[3]{7{,}3 * 7{,}3 * 14{,}6} = 9{,}19\ m$$

**Two Circuit – 3**, with distances of 6m horizontally between A and a, B and b and C and c, and distances of 4,5m vertically between a, b and c and A, B and C.

In the case of double circuits, the equivalent diameter formula changes to $D_e = \frac{D_M * D_{M2}}{D_{M1}}$

$$D_M = \sqrt[3]{D_{AC} * D_{AB} * D_{BC}} = \sqrt[3]{4{,}5 * 4{,}5 * 9} = 5{,}66\ m$$

$$D_{M1} = \sqrt[3]{D_{Aa} * D_{Bb} * D_{Cc}} = \sqrt[3]{6 * 6 * 6} = 6{,}00\ m$$

$$D_{M2} = \sqrt[3]{D_{Ab} * D_{Ac} * D_{Bc}} = \sqrt[3]{7{,}5 * 7{,}5 * 10{,}82} = 8{,}47\ m$$

$$D_e = \frac{D_M * D_{M2}}{D_{M1}} = \frac{5{,}66 * 8{,}47}{6{,}00} = 7{,}99\ m$$

**Two Circuit – 4**, with distances of 20m horizontally between A and a, 7m horizontally between B and C and b and c, 13m horizontally between C and b and 9,2m vertically from A and a to B, C, b and c. In this case, the double circuit is not symmetrical, due to which the calculation coefficients are slightly different to case 3.

$$D_M = \sqrt[3]{D_{AC} * D_{AB} * D_{BC}} = \sqrt[3]{7 * 9{,}84 * 9{,}84} = 8{,}79\ m$$

$$D_{M1} = \sqrt[3]{D_{Aa} * D_{Bb} * D_{Cc}} = \sqrt[3]{20 * 20 * 20} = 20{,}00\ m$$

$$D_{M2} = \sqrt[6]{D_{Ab} * D_{Ac} * D_{Bc} * D_{Ba} * D_{Ca} * D_{Cb}}$$
$$= \sqrt[6]{18{,}89 * 25{,}24 * 27 * 25{,}24 * 18{,}89 * 13} = 20{,}75\ m$$

$$D_e = \frac{D_M * D_{M2}}{D_{M1}} = \frac{8{,}79 * 20{,}75}{20{,}00} = 9{,}12m$$

Taking these calculations into account, we can calculate, using Equation 5 and Equation 6, the difference in reactance for a given line. This is useful as it might shed some light as to certain trends that might be observed in the following chapter. For arguments sake, the line considered has only one copper-aluminium alloy conductor per phase and has an equivalent radius of 10 mm.

$$L_{K1} = \left[\frac{\mu}{2 \cdot n} + 4{,}6 \cdot \log\left(\frac{D_e}{r_e}\right)\right] \cdot 10^{-4} = \left[\frac{1}{2 \cdot 1} + 4{,}6 \cdot \log\left(\frac{9110}{10}\right)\right] \cdot 10^{-4}$$
$$= 1{,}461 * 10^{-3}$$

$$L_{K2} = \left[\frac{\mu}{2 \cdot n} + 4{,}6 \cdot \log\left(\frac{D_e}{r_e}\right)\right] \cdot 10^{-4} = \left[\frac{1}{2 \cdot 1} + 4{,}6 \cdot \log\left(\frac{9190}{10}\right)\right] \cdot 10^{-4}$$
$$= 1{,}413 * 10^{-3}$$

$$L_{K3} = \left[\frac{\mu}{2 \cdot n} + 4{,}6 \cdot \log\left(\frac{D_e}{r_e}\right)\right] \cdot 10^{-4} = \left[\frac{1}{2 \cdot 1} + 4{,}6 \cdot \log\left(\frac{7990}{10}\right)\right] \cdot 10^{-4}$$
$$= 1{,}385 * 10^{-3}$$

$$L_{K4} = \left[\frac{\mu}{2 \cdot n} + 4{,}6 \cdot \log\left(\frac{D_e}{r_e}\right)\right] \cdot 10^{-4} = \left[\frac{1}{2 \cdot 1} + 4{,}6 \cdot \log\left(\frac{9120}{10}\right)\right] \cdot 10^{-4}$$
$$= 1{,}412 * 10^{-3}$$

Calculations have been made to calculate the relative difference there is between lines of different configurations and cables, which can be observed in the appendix.

### 2.2.3. Capacitive Susceptance (B)

Transmission lines are always composed of more than one conductor, one for each phase. As the different conductors of a three-phase power line are constantly at different voltages and insulated between each other, they act as a capacitor. This parameter has quite a high importance as it is linked to reactive power generation and accumulation. The capacity formulation is described in Equation 7.

$$C_K = \left[\frac{24{,}2}{\log\left(\frac{D_e}{r_e}\right)}\right] \cdot 10^{-9} \left[\frac{F}{Km}\right]$$

**Equation 7: Capacity formulation**

where $D_e$ and $r_e$ take the same values as they do in the calculation of reactance.

The capacitive susceptance, in Siemens, for a given line is dependant to the frequency of the power transmitted through said line, meaning that equal lines will have different capacitive susceptances in the European Union, where nominal frequency is 50 Hz, and in the United States, where it is 60 Hz. Its formulation can be observed in Equation 8.

$$B = C_K \cdot \omega = C \cdot 2 \cdot \pi \cdot f \ [S]$$

**Equation 8: Capacitive Susceptance formulation**

## 2.3. Analysis of data published by ENTSO-E

ENTSO-E publishes every two years a ten-year network development plan, for which it includes the electric data the different TSO's provide and aggregates them into a large public database. This database does not include any location data for the different substations or power plants, but it does include resistance, reactance, capacity and thermal rating for the different lines, as well as the voltage at which they work. As the distance the lines cover is not contained within this data, the parameters are compared on a relative basis, by creating ratios of parameters that might provide some colour as to the nature of the lines.

### 2.3.1. Resistance

In transmission networks, mainly two voltage levels are used; 220 kV and 400 kV. Other voltage levels may be found in different countries or transmission technologies, i.e. HVDC.

There are some lines that work at intermediate voltages, but a considerable minority. In fact, there is only one line from Spain to France, that works at 330 kV, and two lines at 500 kV that travel within Italy and from Italy to Montenegro, all of which are HVDC lines. There are four other lines between western European countries, Poland, Hungary, Romania and Ukraine, that work at 750 kV. As these are not common within the European transport system, they have not been considered in the evaluated data, only AC lines at 220 kV or 400 kV.

With a view to fulfilling the objectives of this project, line parameters are always compared considering voltage level and location, that is, based on the country they belong to.

Comparing the data illustrated in Figure 5 and Figure 6, it can be observed how the resistances for lines at 400 kV are generally very similar to those of lines at 220 kV.

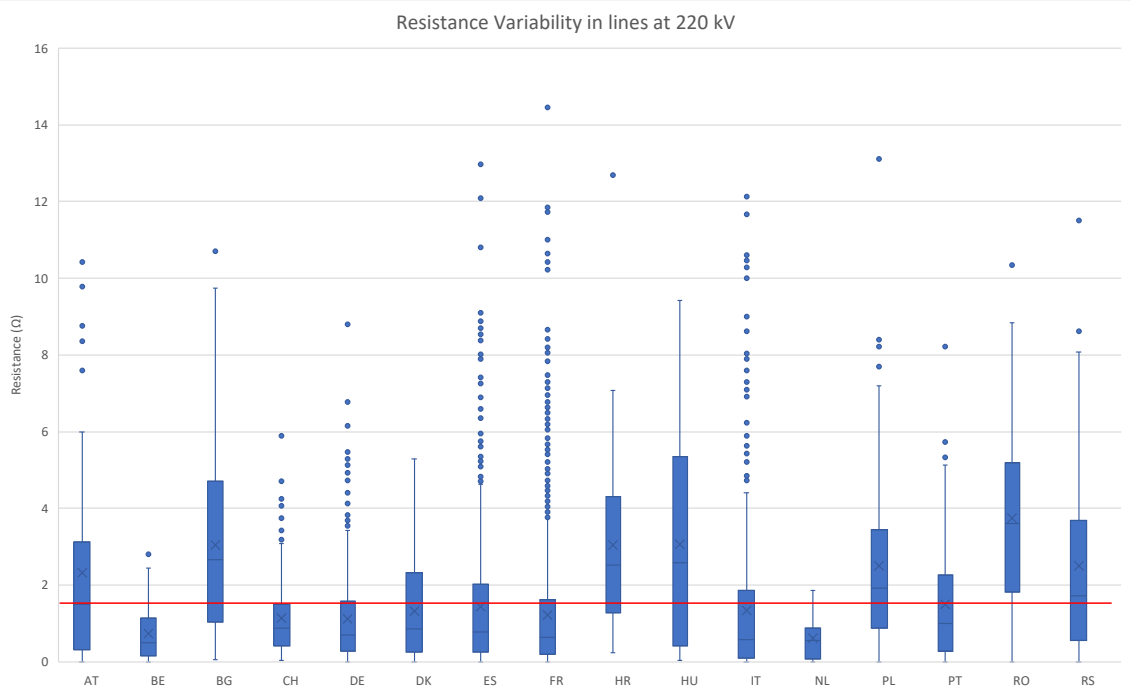



**Figure 5: Resistance variability in lines at 220 kV**

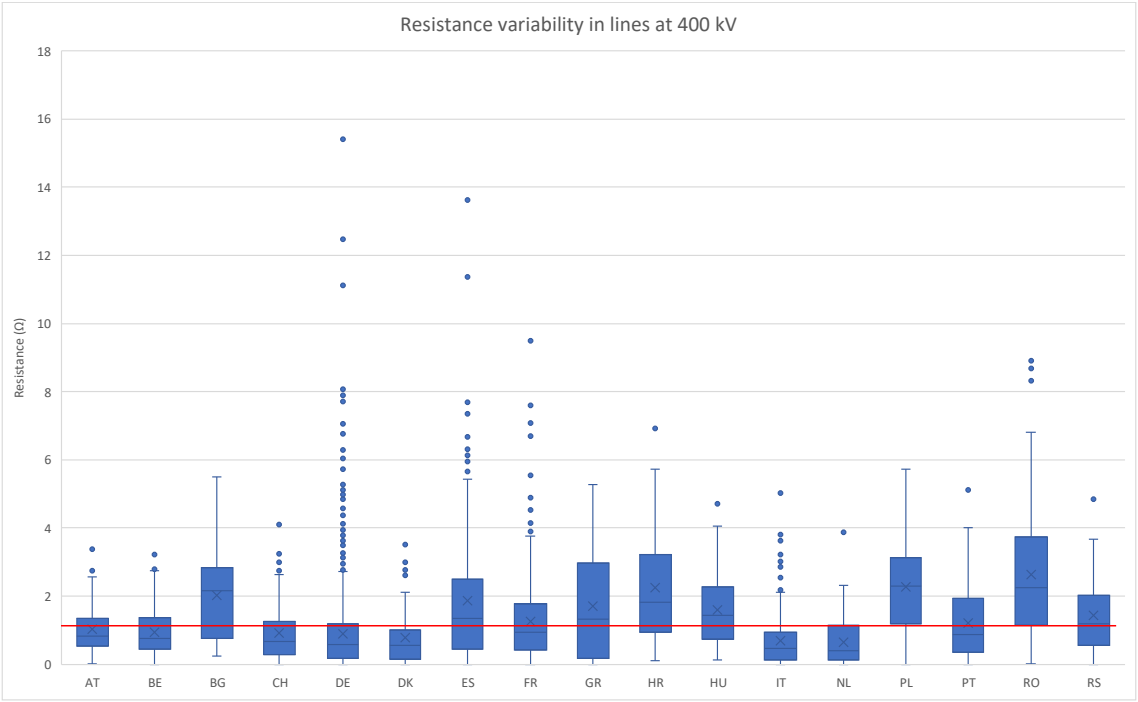



**Figure 6: Resistance variability in lines at 400 kV**

The data summarised in Table 1 and Table 2 shows the maximum, minimum, average and standard deviation of the resistances of the lines within different countries. The values confirm what was suggested above, with slightly lower resistances for lines at 400 kV, but most importantly, with a smaller variability, as can be observed by a smaller average standard deviation.

In the tables, it can also be observed that there are 12 out of 16 countries whose minimum resistance is zero. This could be due to two main reasons. Firstly, it could be due to model assumptions, or secondly, it could be simply due to lack of information. In the latter case, this information should become more trustworthy as time progresses and countries provide better network data in an effort to become more transparent.

It is interesting to highlight the values of reactance and capacitive susceptance for resistances with a value of 0 as this might shed some light on the problem highlighted above. Aside from two lines in Spain with reactances of 4,3 Ω and 4,8 Ω, all other lines working at 220 kV have values of reactance and capacitive susceptance below 1 Ω and 10 µS respectively. These two values are very low in comparison with the rest of lines in Europe, as can be observed in Table 6 and Table 12, they are both below the overall 25$^{th}$ percentile. Two lines in Spain also have high values of capacitive susceptance, above 30 µS, standing out as outliers from the rest, which are mainly below 10 µS.

Another feature that can be extracted from the Table 1 and Table 2 is the relative size of the maximum resistances within different countries. At 400 kV, which usually entails the lines that cover the longest distances, Germany, Spain and France have the highest values, which is in line with them being the countries with the largest extensions in Europe. This analysis in lines at 220 kV shows a more uniform spread of lines as most lines at this voltage only reach a certain length, below the maximum length needed within a country. As a quantitative example, the maximum resistance in France is around twice that of Portugal and three times that of Austria at 400 kV. This is in line with the surface area of these three countries, which are in the same decreasing order. With respect to the average R, it is less clear what the trend is.

Regarding the median of the resistances, it might be interesting to observe the concentration of the lines around it, identifying for example the 2nd and 98th percentile. At 400 kV, countries like Italy and Germany have their 75th percentile below the global average, whereas Hungary Portugal and Romania have their 25th percentile above the global average. This might be due to outliers warping the results or to countries having a greater dispersion of their lines throughout their geography, having a more meshed network.

| Country | N. Lines | RMax (ohms | RMin (ohms | Ravg (ohms) | $\sigma$ R (ohms) | Median R | R 25th Perc. | R 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| Austria | 114 | 10,420 | 0,000 | 2,313 | 2,536 | 1,500 | 0,333 | 3,110 |
| Belgium | 37 | 2,798 | 0,000 | 0,729 | 0,737 | 0,486 | 0,170 | 1,035 |
| Bulgaria | 59 | 10,711 | 0,063 | 3,044 | 2,348 | 2,667 | 1,043 | 4,581 |
| Croatia | 31 | 12,686 | 0,240 | 3,036 | 2,523 | 2,527 | 1,364 | 4,191 |
| Denmark | 11 | 5,290 | 0,000 | 1,320 | 1,550 | 0,846 | 0,371 | 1,811 |
| France | 1590 | 14,456 | 0,000 | 1,219 | 1,606 | 0,640 | 0,186 | 1,615 |
| Germany | 503 | 8,793 | 0,000 | 1,117 | 1,227 | 0,701 | 0,273 | 1,565 |
| Greece | - | - | - | - | - | - | - | - |
| Hungary | 30 | 9,420 | 0,032 | 3,070 | 2,693 | 2,590 | 0,465 | 5,178 |
| Italy | 493 | 12,125 | 0,000 | 1,346 | 1,985 | 0,580 | 0,100 | 1,863 |
| Netherlands | 30 | 1,850 | 0,000 | 0,612 | 0,513 | 0,551 | 0,113 | 0,853 |
| Polland | 150 | 13,112 | 0,000 | 2,506 | 2,214 | 1,926 | 0,907 | 3,395 |
| Portugal | 179 | 8,209 | 0,000 | 1,500 | 1,477 | 0,997 | 0,273 | 2,245 |
| Romania | 90 | 10,338 | 0,000 | 3,739 | 2,326 | 3,606 | 1,866 | 5,112 |
| Russia | 75 | 11,600 | 0,000 | 2,492 | 2,601 | 1,710 | 0,558 | 3,662 |
| Spain | 851 | 12,971 | 0,000 | 1,442 | 1,786 | 0,779 | 0,271 | 2,016 |
| Switzerland | 201 | 5,882 | 0,034 | 1,138 | 0,996 | 0,870 | 0,405 | 1,480 |
| **Weighted average** | | | | **1,505** | **1,828** | **0,935** | **0,327** | **2,088** |

**Table 1: Resistance data summary per country for lines at 220 kV**

From Table 1 it is interesting to point out, for example, that France, Poland and Spain have the highest maximum values of resistance whilst their average resistance is not an extreme value, quite the contrary, with France and Spain being almost at the global average. Hungary on the other hand, which has a maximum value of 9,42 Ω, much lower than that of France at 14,546 Ω, has a 75th percentile value which is the highest of the

whole 220 kV data set. Regarding the 25th percentile, it is interesting to note that this value in Bulgaria, Croatia and Romania is also the highest of the whole data set. This could be due to the thermal rating of these lines being smaller, which can be seen in Figure 11 to be a possibility as these countries have all lines up to the 75th percentile below the global average of 553 MVA. It could also be due to these countries having longer lines, but they are not necessarily large countries in comparison with Spain, for example, whose 75th line resistance percentile lies at 2,5 Ω, more than 60% under that of Bulgaria at 5,112 Ω.

| Country | N. Lines | RMax (ohms) | RMin (ohms) | Ravg (ohms) | $\sigma$ R (ohms) | Median R | R 25th Perc. | R 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| Austria | 62 | 3,379 | 0,024 | 1,023 | 0,798 | 0,826 | 0,531 | 1,333 |
| Belgium | 79 | 3,230 | 0,000 | 0,946 | 0,709 | 0,762 | 0,437 | 1,369 |
| Bulgaria | 46 | 5,504 | 0,240 | 2,026 | 1,318 | 2,160 | 0,920 | 2,787 |
| Croatia | 26 | 6,927 | 0,102 | 2,238 | 1,670 | 1,829 | 1,119 | 3,174 |
| Denmark | 72 | 3,524 | 0,000 | 0,788 | 0,873 | 0,546 | 0,144 | 0,982 |
| France | 458 | 9,499 | 0,000 | 1,253 | 1,201 | 0,948 | 0,419 | 1,765 |
| Germany | 1226 | 15,405 | 0,000 | 0,900 | 1,236 | 0,582 | 0,170 | 1,198 |
| Greece | 114 | 5,264 | 0,000 | 1,699 | 1,602 | 1,322 | 0,180 | 2,960 |
| Hungary | 57 | 4,720 | 0,126 | 1,590 | 1,010 | 1,433 | 0,741 | 2,229 |
| Italy | 373 | 5,101 | 0,000 | 0,695 | 0,790 | 0,467 | 0,125 | 0,934 |
| Netherlands | 83 | 3,872 | 0,000 | 0,637 | 0,655 | 0,400 | 0,165 | 1,051 |
| Polland | 105 | 5,728 | 0,000 | 2,276 | 1,340 | 2,288 | 1,200 | 3,104 |
| Portugal | 97 | 5,126 | 0,000 | 1,201 | 1,070 | 0,864 | 0,368 | 1,936 |
| Romania | 80 | 8,896 | 0,016 | 2,622 | 1,939 | 2,240 | 1,156 | 3,724 |
| Russia | 53 | 4,840 | 0,000 | 1,433 | 1,108 | 1,180 | 0,597 | 1,969 |
| Spain | 346 | 13,620 | 0,000 | 1,874 | 1,878 | 1,352 | 0,442 | 2,492 |
| Switzerland | 74 | 4,099 | 0,000 | 0,922 | 0,847 | 0,675 | 0,317 | 1,235 |
| **Weighted average** | | | | **1,201** | **1,224** | **0,903** | **0,355** | **1,661** |

**Table 2: Resistance data summary per country for lines at 400 kV**

Another interesting relation where resistance can be analysed is between the line capacity, or thermal rating as ENTSO-E refers to it, and resistance. As can be observed in Figure 7 and Figure 8, the relationship resembles that of an inverse square, which shows an increasing thermal rating as resistance decreases. This is logical as high resistances limit the amount of current due to ohmic heat generation. It is interesting to note there is a high number of zero values, both in resistance and thermal rating. Both a zero resistance and a zero thermal rating have no meaning in reality, as a zero resistance would allow an infinite thermal rating, and a zero thermal rating would be a useless line. These values are probably due to faulty information. A zero resistance might be due to model assumptions as mentioned before but there is no way of checking efficiently whether these lines are that without the full PSSE model. One of these values could be approximated once the other is estimated, which could be done using reactance, if there was a possible relation, as this data point is given to all lines.

ENTSO-E does not provide length data for lines, but it might be interesting to observe whether the longest lines have the lowest resistances per kilometre, possibly due to having more than one conducting circuit. Spain, Portugal and France provide distance data for their lines, which will be explored in the next chapter.

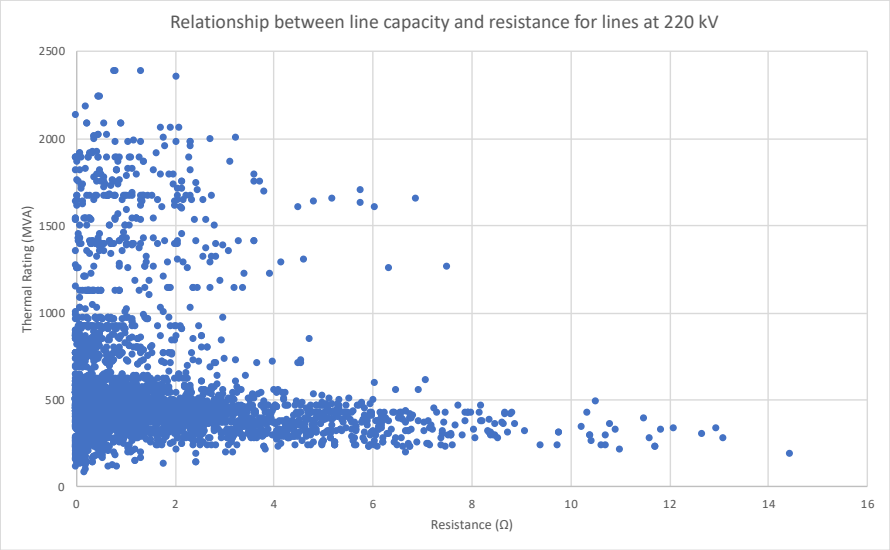



**Figure 7: Relationship between thermal rating and resistance for lines at 220 kV**

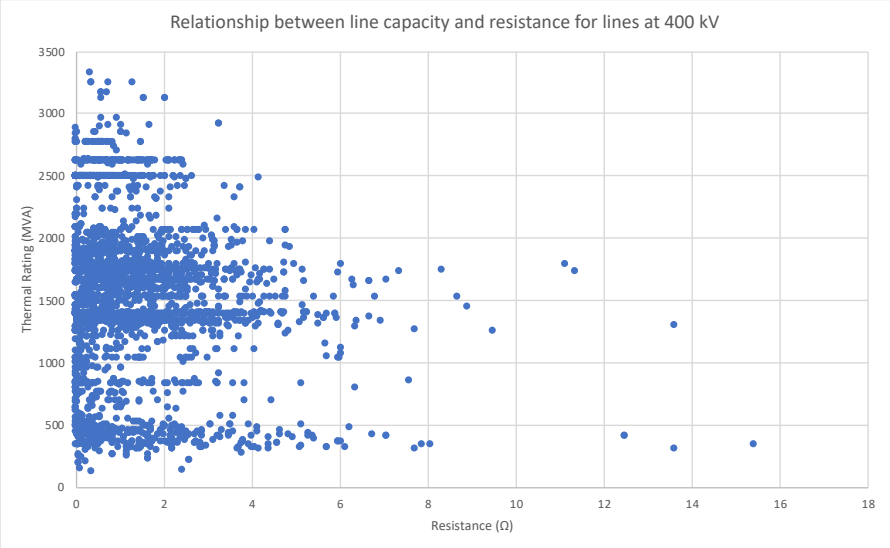



**Figure 8: Relationship between thermal rating and resistance for lines at 400 kV**

It can be noted that the highest value of thermal rating for lines at 400 kV corresponds to a somewhat clear outlier as it is a line in Greece with no resistance and a thermal rating value of 9999 A. The clustered data mainly hovers around 500 A in Figure 7 whereas the values in Figure 8 are more scattered but more aligned within very similar thermal ratings for a broad number of resistances.

Finally, regarding the possible estimation of resistance from thermal rating it might be interesting to identify possible relations with a histogram, as can be observed in and

Figure 9. The thermal-rating zero values are located in Spain, Italy and Portugal only for 220 kV. For lines at 400 kV they are located in a broad variety of countries; Belgium, Germany, Denmark, Spain, France, Greece, Italy, the Netherlands, Portugal and Poland.

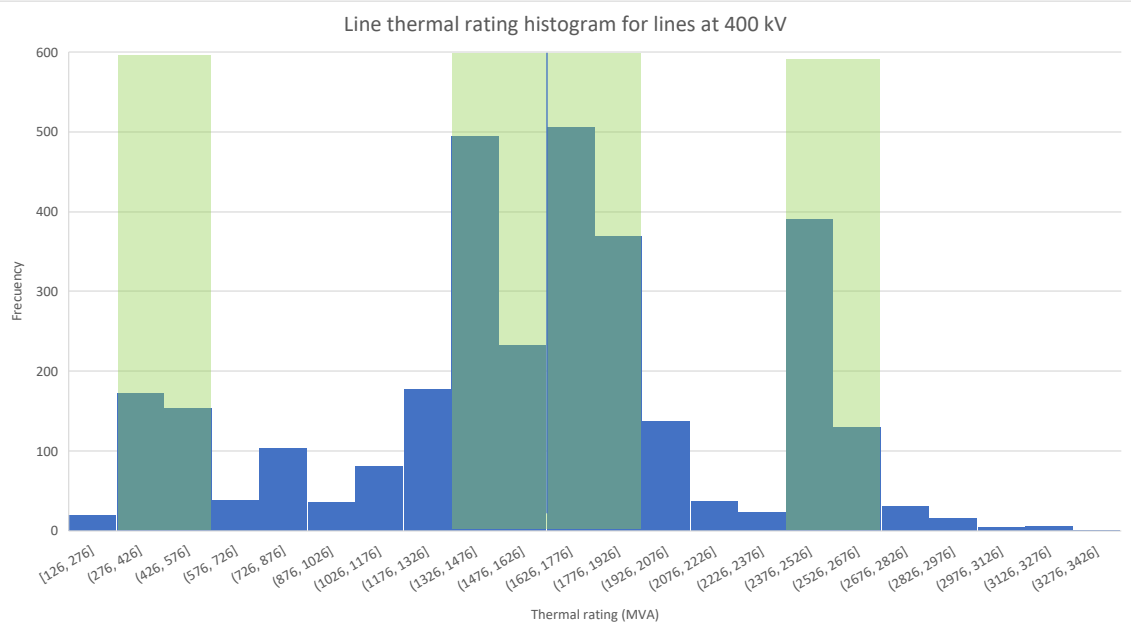



**Figure 9: Thermal rating Histogram for lines at 400 kV.**

If four clusters are made from the histogram, the resulting resistance information from those four main clusters and three intermediate clusters and their variability is summarized in Table 3. The main clusters have been highlighted.

| | 276-576 | 576-1176 | 1176-1550 | 1550-2076 | 2076-2376 | 2376-2676 | 2676-3426 |
|---|---|---|---|---|---|---|---|
| R Max | 15,405 | 7,590 | 9,499 | 11,360 | 3,632 | 4,154 | 3,261 |
| R Min | 0,008 | 0,007 | 0,008 | 0,002 | 0,037 | 0,002 | 0,010 |
| R Average | 1,861 | 1,178 | 1,604 | 1,335 | 1,092 | 0,794 | 0,762 |
| R St. Dev | 2,150 | 1,484 | 1,540 | 1,208 | 0,937 | 0,644 | 0,677 |
| N. of Lines | 315 | 196 | 638 | 1060 | 47 | 451 | 59 |

**Table 3: Resistance statistics for different thermal rating clusters for lines at 400 kV**

A clear trend of decreasing resistance with increasing thermal rating becomes apparent. Decreasing variability, standard deviation, with increasing thermal rating might be indicative of a possible means of identifying resistance ranges for synthetic networks. This trend is very practical and logical as having high resistances at high power transfer scenarios would cause a high degree of losses. The number of equivalent circuits is not contemplated in the information provided by ENTSO-E in the TYNDP of 2016 but it was in the case of 2014 and will be used in the following chapter to explore the significance

of multiple circuits. Table 4 shows the distribution of line thermal ratings per country for lines at 400 kV.

| Country | 276-576 | 576-1176 | 1176-1550 | 1550-2076 | 2076-2376 | 2376-2676 | 2676-3426 |
|---|---|---|---|---|---|---|---|
| Austria | 0% | 0% | 18% | 56% | 0% | 26% | 0% |
| Belgium | 27% | 3% | 39% | 19% | 0% | 0% | 13% |
| Bulgaria | 7% | 9% | 85% | 0% | 0% | 0% | 0% |
| Croatia | 0% | 27% | 73% | 0% | 0% | 0% | 0% |
| Denmark | 25% | 31% | 14% | 26% | 0% | 0% | 5% |
| France | 1% | 5% | 10% | 42% | 3% | 35% | 4% |
| Germany | 12% | 4% | 12% | 41% | 2% | 28% | 0% |
| Greece | 7% | 12% | 71% | 10% | 0% | 0% | 0% |
| Hungary | 4% | 21% | 74% | 0% | 0% | 2% | 0% |
| Italy | 58% | 15% | 15% | 8% | 4% | 0% | 0% |
| Netherlands | 2% | 4% | 14% | 44% | 5% | 2% | 28% |
| Polland | 4% | 20% | 36% | 40% | 0% | 0% | 0% |
| Portugal | 24% | 4% | 26% | 42% | 4% | 0% | 0% |
| Romania | 0% | 4% | 61% | 26% | 4% | 0% | 5% |
| Russia | 0% | 6% | 94% | 0% | 0% | 0% | 0% |
| Spain | 21% | 11% | 22% | 44% | 0% | 1% | 1% |
| Switzerland | 0% | 5% | 7% | 78% | 5% | 3% | 1% |

**Table 4: Thermal rating statistics for different countries for lines at 400 kV**

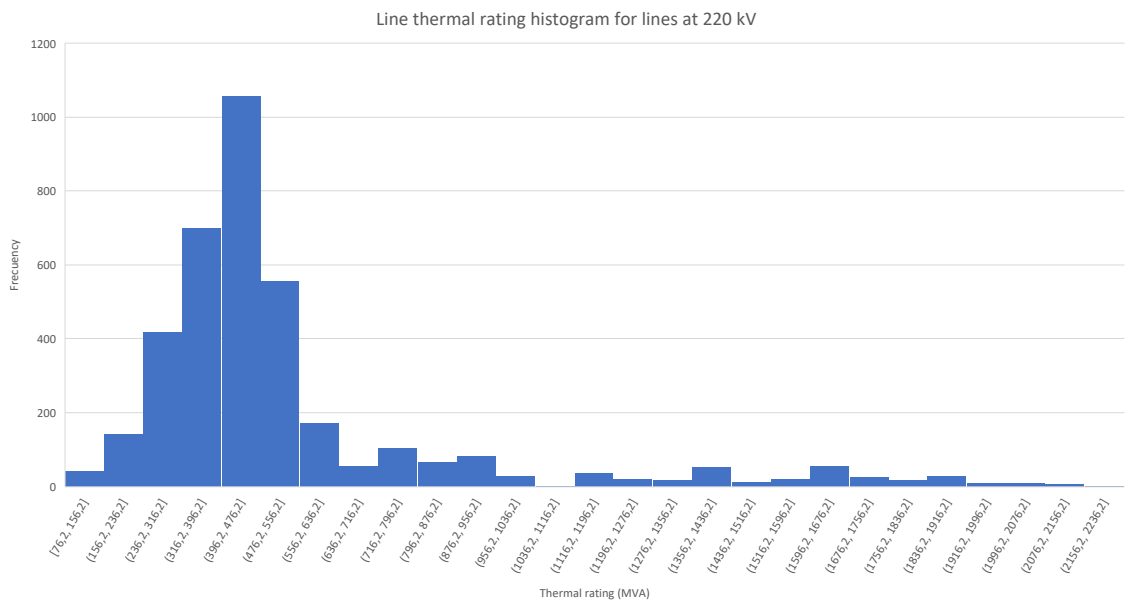



**Figure 10: Thermal rating Histogram for lines at 220 kV.**

In the case of lines working at 220 kV, there emerges only one clear range, with thermal rating values below 1000 MVA. This data has a mean of 682 MVA, with a standard deviation of 674 MVA, meaning the data observed for the statistics in Table 5 has only been taken for lines with thermal rating below two standard deviations away from the mean, that is, below 2030 A. The data above 650 MVA has the possibility of having a different unit to amperes. As this data is provided by a variety of TSO's, there is a high chance the capacity of the lines is provided in MVA's instead of Amps.

| | |
|---|---|
| Min | 0,000 |
| Max | 14,456 |
| Average | 1,549 |
| St. Dev | 1,824 |
| N. of Lines | 3656 |

**Table 5: Resistance statistics for single thermal rating cluster for lines at 220 kV**

With respect to this, it can be observed in Figure 11 the variability of thermal rating throughout the different countries. Figure 12 shows the variability in lines at 400 kV, whose values are generally higher as would be expected.

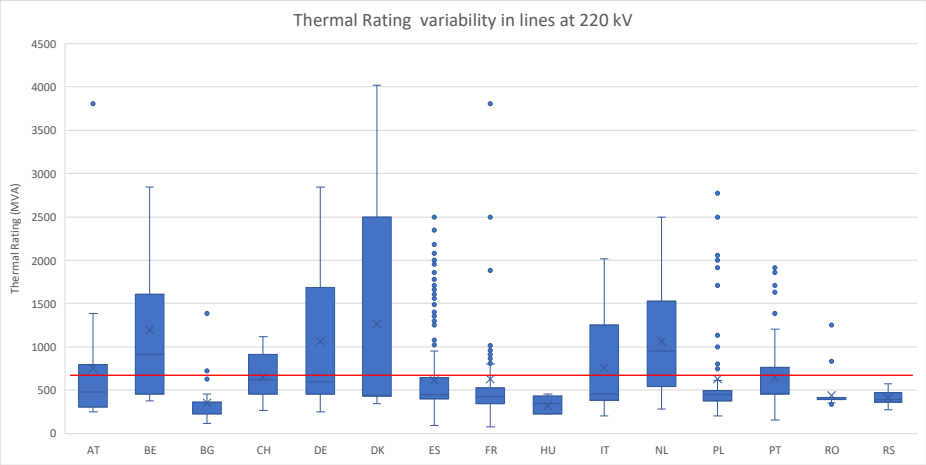



**Figure 11: Thermal Rating Variability in lines at 220kV**

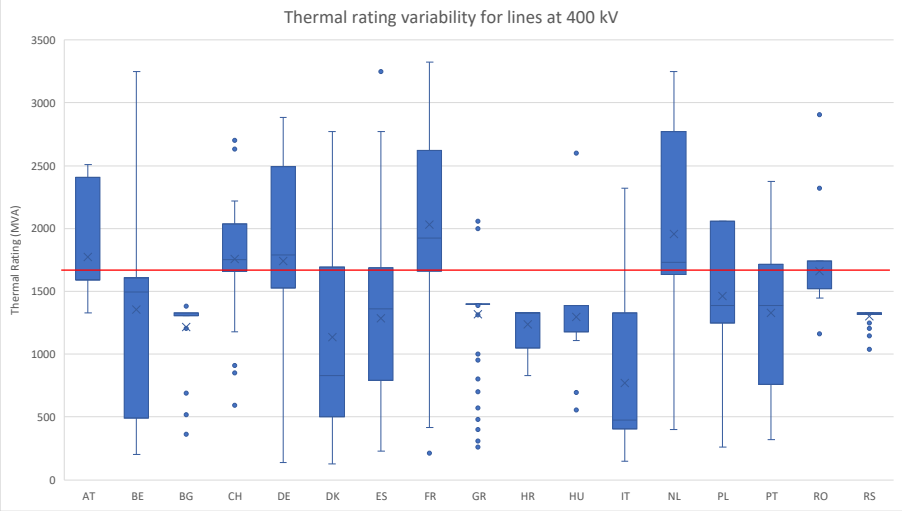



**Figure 12: Thermal Rating Variability in lines at 400kV**

This high variability in the thermal ratings of the different countries proves hard to thresh. It is quite challenging to identify individually what each country has used, but to try and identify the meaning of these in Spain and France, a comparison with official data published by their respective governments is useful. In France, the official data published by RTE, the French TSO, for lines at 220 kV shows a mean power transfer in a winter

scenario of 1100 A, which equates to approximately 420 MVA. From the data observable in Figure 11, it can be observed that this plot corresponds to MVA and not amps as is stated in the provided spreadsheet. Likewise, in Spain, the data published on the BOE regarding transmission lines at 220 kV mentions a power transfer rate of around 300 MVA [4], 500 and 650 MVA [6]. These values are also approximately in line with the data provided in ENTSO-E, only that they are in MVA and ENTSO-E quotes them as Amps. Equations 9 show how the conversion factor between amps and MVA is calculated.

$$\sqrt{3} * U[kV] * I[A] = S[MVA] * 10^3 \rightarrow \frac{\sqrt{3} * U[kV]}{10^3} * I[A] = S[MVA]$$

$$\frac{\sqrt{3} * 220}{10^3} = 0{,}381 \quad \text{or} \quad \frac{\sqrt{3} * 400}{10^3} = 0{,}693$$

**Equations 9: MVA-A Conversion factor for line thermal rating**

These resistances are fairly clustered together, being one able to use these numbers comfortably to predict resistance for lines at 220 kV with a relatively high degree of confidence in synthetic networks.

### 2.3.2. Reactance

As with resistance, voltages have been separated to the same 220 and 400 kV clusters to try to identify possible differences but at plain site it is not apparent how the reactances of the lines differ. As explored before, reactance of a line is dependent on material, number of conductors and line geometry, as well as total distance of the line, meaning larger reactances should be observed for larger countries, especially within lines at 400 kV as these tend to cover larger distances.

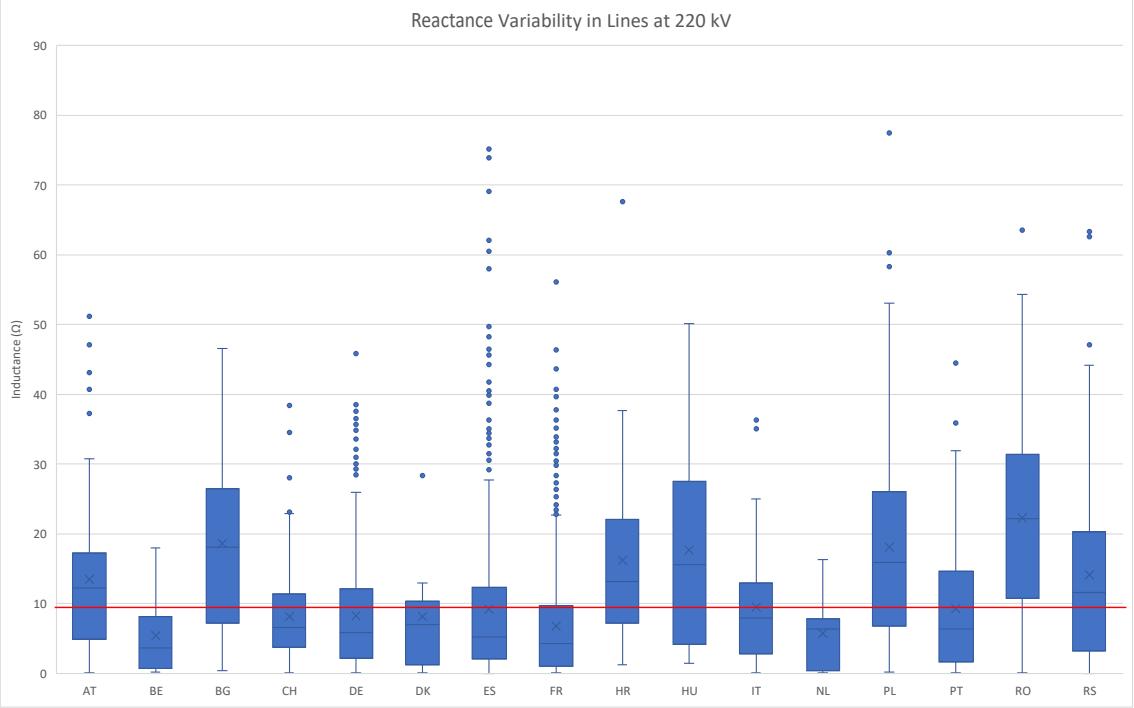



**Figure 13: Reactance Variability for lines at 220 kV**

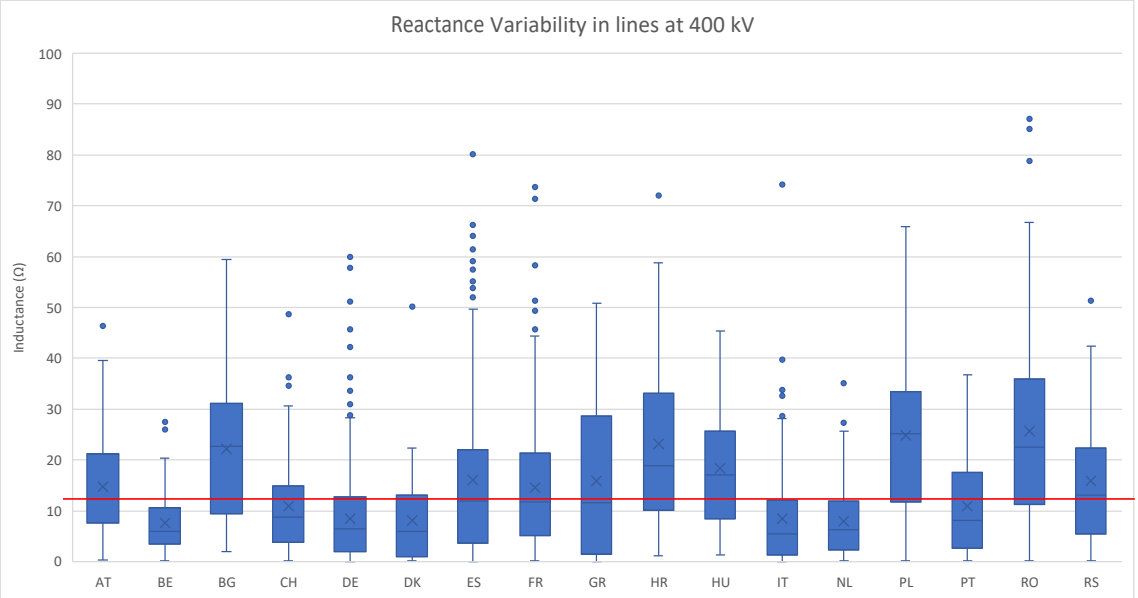



**Figure 14: Reactance Variability for lines at 400 kV**

The data observed in Figure 13 and Figure 14 shows very similar values of line reactance, with the only observable difference at this point being the slightly larger values for reactance in lines at 220 kV. This is as expected but is a very small difference. The number of outliers, on the other hand, does decrease significantly at 400 kV. This could mean more trustworthy data for lines at this voltage level.

Unlike in the resistance data, there are no lines that have a zero value for reactance.

The relative size of the reactances between countries is also interesting to mention as there is much less variability than with resistance. In this case, all countries hover around the global average, with only Belgium, Germany, Denmark, Italy and the Netherlands having their 75$^{th}$ percentile value below or very near the global average. In this case therefore, the same principle of country surface area being slightly proportional to resistance does not apply to reactance.

| Country | N. Lines | XMax (ohms) | XMin (ohms) | Xavg (ohms) | $\sigma$ X (ohms) | Median X | X 25th Perc. | X 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| Austria | 114 | 51,200 | 0,048 | 13,446 | 12,074 | 12,200 | 5,000 | 16,741 |
| Belgium | 37 | 30,739 | 0,160 | 6,366 | 6,781 | 3,656 | 1,475 | 8,162 |
| Bulgaria | 59 | 46,546 | 0,387 | 18,615 | 12,249 | 18,063 | 8,470 | 26,126 |
| Croatia | 31 | 67,659 | 1,231 | 16,219 | 13,282 | 13,182 | 7,282 | 22,046 |
| Denmark | 11 | 28,401 | 0,054 | 8,113 | 8,076 | 7,005 | 2,567 | 10,345 |
| France | 1590 | 56,100 | 0,048 | 6,699 | 7,727 | 4,162 | 0,978 | 9,522 |
| Germany | 503 | 45,835 | 0,048 | 8,216 | 7,872 | 5,831 | 2,112 | 12,052 |
| Hungary | 30 | 50,090 | 0,272 | 17,100 | 14,646 | 14,100 | 3,600 | 27,032 |
| Italy | 493 | 71,920 | 0,048 | 8,784 | 11,996 | 4,180 | 0,604 | 11,546 |
| Netherlands | 30 | 16,269 | 0,048 | 6,029 | 4,633 | 6,370 | 0,571 | 7,972 |
| Poland | 150 | 77,401 | 0,160 | 17,674 | 14,254 | 15,389 | 6,478 | 26,004 |
| Portugal | 179 | 44,455 | 0,048 | 9,227 | 8,989 | 6,350 | 1,774 | 14,617 |
| Romania | 90 | 63,535 | 0,102 | 22,329 | 14,076 | 22,148 | 10,809 | 30,983 |
| Russia | 75 | 63,350 | 0,000 | 14,126 | 13,924 | 11,570 | 3,283 | 20,191 |
| Spain | 851 | 75,152 | 0,006 | 9,151 | 10,896 | 5,150 | 2,033 | 12,238 |
| Switzerland | 201 | 38,393 | 0,128 | 8,173 | 6,433 | 6,580 | 3,780 | 11,390 |
| **Weighted average** | | | | **9,016** | **10,309** | **6,146** | **2,119** | **12,605** |

**Table 6: Reactance data summary per country for lines at 220 kV**

| Country | N. Lines | XMax (ohms | XMin (ohms | Xavg (ohms) | $\sigma$ X (ohms) | Median X | X 25th Perc. | X 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| Austria | 62 | 46,299 | 0,334 | 14,749 | 11,458 | 12,197 | 7,594 | 20,515 |
| Belgium | 79 | 27,552 | 0,160 | 7,613 | 5,855 | 6,006 | 3,475 | 10,506 |
| Bulgaria | 46 | 59,520 | 1,968 | 22,149 | 14,998 | 22,720 | 11,340 | 31,000 |
| Croatia | 26 | 72,041 | 1,086 | 23,123 | 17,245 | 18,914 | 11,879 | 32,667 |
| Denmark | 72 | 50,094 | 0,160 | 8,147 | 8,456 | 5,944 | 1,068 | 12,634 |
| France | 458 | 73,670 | 0,102 | 14,512 | 12,676 | 11,667 | 5,364 | 21,245 |
| Germany | 1226 | 59,976 | 0,048 | 8,375 | 8,133 | 6,402 | 2,007 | 12,739 |
| Greece | 114 | 50,848 | 0,048 | 15,871 | 15,068 | 11,629 | 1,580 | 28,656 |
| Hungary | 57 | 45,299 | 1,381 | 18,310 | 11,042 | 17,104 | 8,450 | 25,606 |
| Italy | 373 | 74,250 | 0,048 | 8,445 | 9,332 | 5,414 | 1,299 | 11,976 |
| Netherlands | 83 | 35,136 | 0,160 | 7,968 | 7,295 | 6,302 | 2,369 | 11,912 |
| Poland | 105 | 65,952 | 0,096 | 24,807 | 14,738 | 25,120 | 12,496 | 32,816 |
| Portugal | 97 | 36,800 | 0,111 | 10,940 | 9,806 | 8,112 | 2,715 | 16,944 |
| Romania | 80 | 87,104 | 0,176 | 25,588 | 18,738 | 22,432 | 11,340 | 35,384 |
| Russia | 53 | 51,310 | 0,160 | 15,895 | 12,350 | 13,088 | 6,981 | 21,029 |
| Spain | 346 | 80,144 | 0,048 | 16,012 | 15,303 | 11,840 | 3,641 | 21,992 |
| Switzerland | 74 | 48,600 | 0,160 | 10,990 | 9,663 | 8,703 | 3,875 | 14,454 |
| **Weighted average** | | | | **12,000** | **12,103** | **9,515** | **3,674** | **17,467** |

**Table 7: Reactance data summary per country for lines at 400 kV**

The data on Table 6 and Table 7 confirms what was suggested before. Values are very similar for different voltages, with the being slightly higher for lines at 400 kV, in line with them having longer distances and reactance being a longitudinal parameter. Although reactance is a parameter that depends on the topology of the line, topology

throughout the lines at a voltage level varies less than between voltage levels, allowing us to talk about reactance as a longitudinal characteristic when comparing voltage levels.

It might be interesting to evaluate the relationship between thermal rating of a line and its reactance. In AC lines, reactance is a limiting parameter at high power transfers, which is what led to engineers developing High Voltage Direct Current lines, on paper an idea which would result in much higher losses due to ohmic resistance but which compensated for those due to the limitations of reactive power and the skin effect. The limitation imposed by reactive power can be easily observed in Equation 10, as larges reactances reduce the power carrying capacity.

$$P = \frac{\theta_A - \theta_B}{X}$$

**Equation 10: Power transmitted through a line**

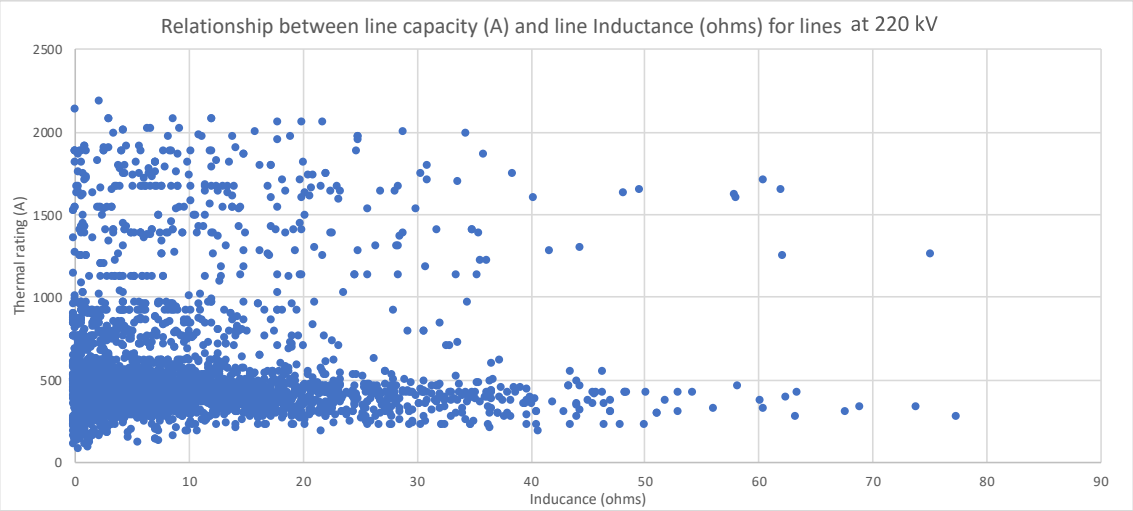



**Figure 15: Relationship between thermal rating and reactance for lines at 220 kV**

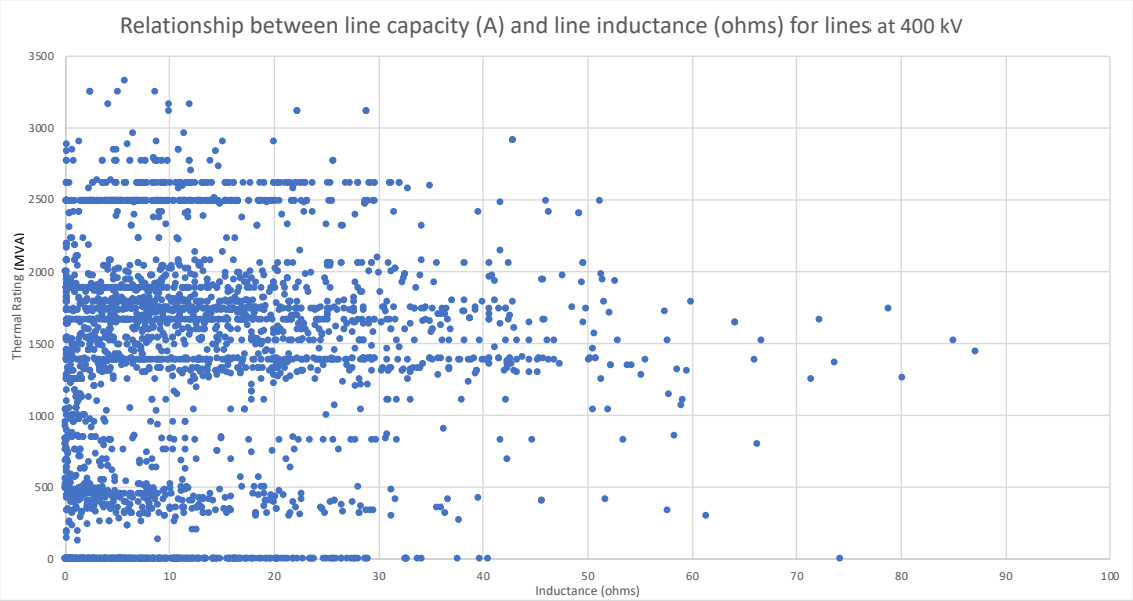



**Figure 16: Relationship between thermal rating and reactance for lines at 400 kV**

Figure 15 illustrates a clear cluster of lines around the 500 MVA thermal rating, which is a useful data point, but shows an almost identical relation to that of resistance and thermal rating, as do the relationships between thermal rating and reactance at 400 kV in Figure 16. Both these simillarities are indicative of the proportional nature of resistance and reactance with distance, which might indicate studying the relation between resistance and impedance directly might shed light on possible line identifications.

As with resistance, and alluding to the different clusters identified in Figure 9 and Figure 10, it is interesting to observe if the different clusters show any clear trend in terms of reactance. The data in Table 8 and Table 9 illustrates the results

| | |
|---|---|
| Min | 0,000 |
| Max | 77,401 |
| Average | 9,404 |
| St. Dev | 10,280 |
| N. of Lines | 3621 |

**Table 8: Reactance statistics for single thermal rating cluster for lines at 220 kV**

| | 276-576 | 576-1176 | 1176-1550 | 1550-2076 | 2076-2376 | 2376-2676 | 2676-3426 |
|---|---|---|---|---|---|---|---|
| X Max | 61,376 | 66,272 | 87,104 | 78,784 | 41,746 | 51,200 | 42,869 |
| X Min | 0,048 | 0,048 | 0,160 | 0,128 | 0,160 | 0,160 | 0,160 |
| X Average | 9,571 | 10,765 | 15,886 | 13,217 | 10,122 | 10,244 | 10,395 |
| X St. Dev | 10,063 | 14,430 | 15,414 | 11,540 | 10,331 | 8,941 | 9,135 |
| N. of Lines | 319 | 215 | 665 | 1098 | 58 | 522 | 61 |

**Table 9: Reactance statistics for thermal rating clusters for lines at 400 kV**

Firstly, it is important to point out the difference in the number of lines. This is due to the elimination of the zero values in resistance. Reactance data has no zero values. Secondly, whilst in Table 8 it is possible to see a clear peak of reactances, in Table 9 there is less of a clear trend relating thermal rating and reactance. The average reactance is higher in the lines between 800 MVA and 2300 MVA than it is for those with a higher or lower thermal rating.

As stated before, as there is a tight connection between resistance and reactance, it could be interesting to analyse the relationship between both. The issue arises when exploring the information provided globally, distinguishing only by voltages. The data obtained is too noisy and not enough detail can be extracted from it, as can be observed in Figure 17 and Figure 18.

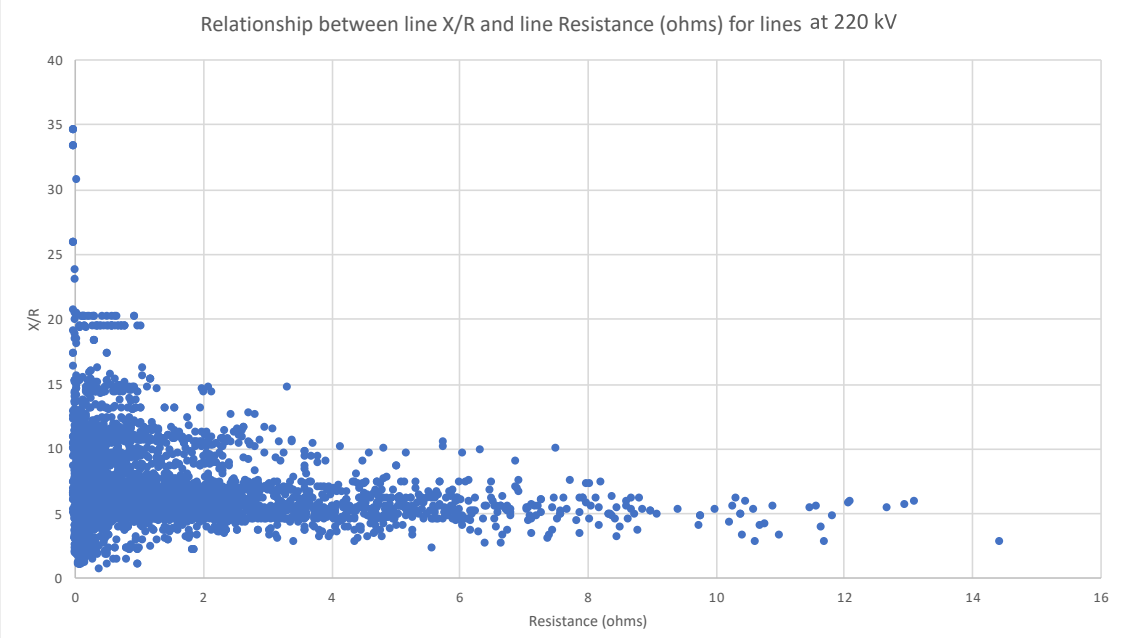



**Figure 17: Relationship between X/R and resistance in lines at 220 kV**

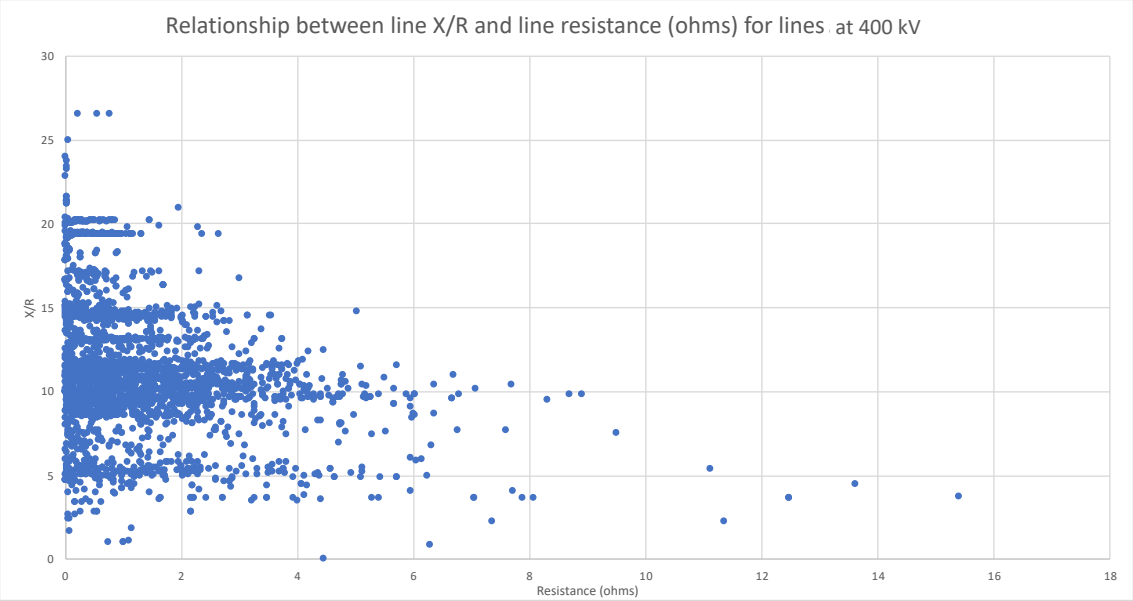



**Figure 18: Relationship between X/R and resistance in lines at 400 kV**

Although some trends can be appreciated charts, it is clear a further degree of filtering must occur. In this respect, the easiest way is to separate by countries. Each country displays a from one to three relations between X and R which are isolated and their fit to a straight line is measured calculating the $R^2$ of said fit. The preliminary results obtained can be observed in Table 10.

| | 220 kV | | 400 kV | |
|---|---|---|---|---|
| | N. of X/R | Av. of R^2 | N. of X/R | Av. of R^2 |
| Austria | 1 | 99,00% | 4 | 99,96% |
| Belgium | 4 | 98,46% | 4 | 91,19% |
| Bulgaria | 4 | 99,64% | 3 | 98,60% |
| Denmark | 2 | 98,91% | 2 | 94,60% |
| France | 5 | 99,30% | 6 | 99,75% |
| Germany | 8 | 99,37% | 7 | 99,69% |
| Greece | - | - | 3 | 99,37% |
| Hungary | 2 | 97,54% | 1 | 98,37% |
| Italy | 7 | 99,73% | 4 | 99,62% |
| Netherlands | 1 | 74,42% | 2 | 91,35% |
| Poland | 3 | 99,01% | 2 | 99,38% |
| Portugal | 3 | 98,41% | 3 | 99,06% |
| Romania | 2 | 99,99% | 1 | 99,54% |
| Russia | 2 | 99,72% | 2 | 99,87% |
| Spain | 4 | 97,97% | 2 | 90,62% |
| Switzerland | 7 | 99,07% | 3 | 99,21% |
| **Total** | **55** | **98,64%** | **49** | **97,91%** |

**Table 10: Number of relations between X and R per voltage**

Also, in Table 10, the average fit of the different relations found within each country and voltage is illustrated. As can be seen, the level of fit is overall on average above 90%, reaching 100% in Romania and Russia. This makes the relations very interesting when trying to identify the geometry of the line or make assumptions regarding lines in other countries.

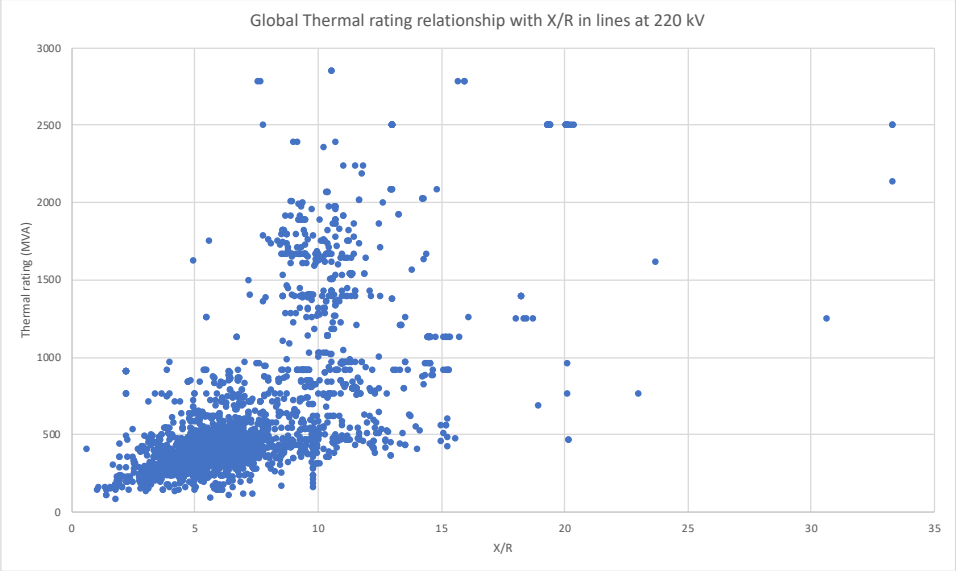



**Figure 19: X/R relation to thermal rating for lines at 220 kV**

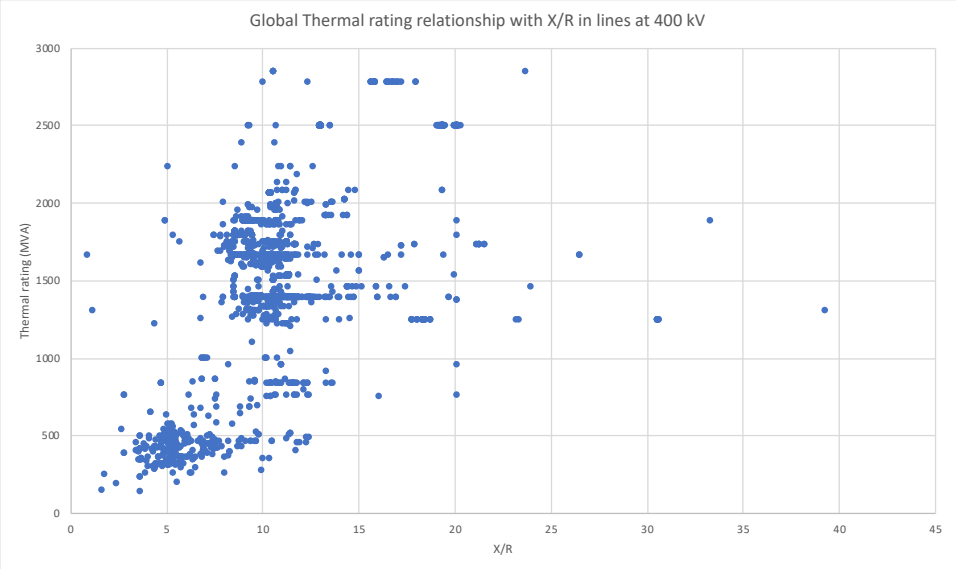



**Figure 20: X/R relation to thermal rating for lines at 400 kV**

The existence of lines with such high thermal ratings at 220 kV in Figure 19 seems anomalous but it can be seen in the figures in the appendix that there is no individual country that has most of its lines at that level. Most countries have some lines with a high capacity at 220 kV and similarly at 400 kV.

As it can be seen in the next chapter in Figure 46 and Figure 47, it seems there is no clear relation between X/R and the thermal rating of a line in any country. It seems for a given ratio there may be several thermal ratings within the same country, leaving the results illustrated in Figure 19 and Figure 20 to be the best indication of a link between X/R and thermal rating. Boundaries can be set at the relation between both, as the ratio of thermal rating over X/R should be between 200 and 33 for lines at 220 kV and between 250 and 50 in lines at 400 kV. These relationships should be taken as mere indications and not as pure restrictions as to what lines characteristics should be.

| 220 kV | | | | 400 KV | | | |
|---|---|---|---|---|---|---|---|
| Country | X/R | R^2 | Multiple | Country | X/R | R^2 | Multiple |
| Austria | 11,2910 | 0,9900 | 1,00x | Austria | 12,6430 | 0,9994 | 1,00x |
| Belgium | 6,6259 | 0,9575 | 1,00x | | 14,1510 | 0,9989 | 1,12x |
| | 9,7720 | 0,9807 | 1,47x | | 17,0580 | 0,9999 | 1,35x |
| | 14,3570 | 1,0000 | 2,17x | | 26,5140 | 1,0000 | 2,10x |
| | 20,1530 | 1,0000 | 3,04x | Belgium | 5,6309 | 0,7011 | 1,00x |
| Bulgaria | 4,0008 | 0,9932 | 1,00x | | 8,7692 | 0,9480 | 1,56x |
| | 6,1387 | 0,9963 | 1,53x | | 10,2890 | 0,9988 | 1,83x |
| | 7,7583 | 1,0000 | 1,94x | | 14,6930 | 0,9998 | 2,61x |
| | 9,2452 | 9,9959 | 2,31x | Bulgaria | 10,3790 | 0,9976 | 1,00x |
| Switzerland | 4,2016 | 0,9772 | 1,00x | | 12,0950 | 0,9760 | 1,17x |
| | 5,5960 | 0,9923 | 1,33x | | 13,9210 | 0,9845 | 1,34x |
| | 6,7564 | 0,9962 | 1,61x | Switzerland | 11,3330 | 0,9865 | 1,00x |
| | 7,5764 | 0,9960 | 1,80x | | 11,5440 | 0,9977 | 1,02x |
| | 8,3715 | 0,9784 | 1,99x | | 15,0400 | 0,9921 | 1,33x |
| | 11,2890 | 0,9975 | 2,69x | Germany | 3,6853 | 0,9934 | 1,00x |
| | 14,6270 | 0,9970 | 3,48x | | 5,2059 | 0,9935 | 1,41x |
| Germany | 3,6774 | 0,9916 | 1,00x | | 8,6794 | 0,9958 | 2,36x |
| | 5,3524 | 0,9708 | 1,46x | | 11,0560 | 0,9967 | 3,00x |
| | 7,5753 | 0,9965 | 2,06x | | 12,9500 | 0,9991 | 3,51x |
| | 9,0668 | 0,9966 | 2,47x | | 19,4150 | 1,0000 | 5,27x |
| | 10,5560 | 0,9959 | 2,87x | | 20,0310 | 0,9998 | 5,44x |
| | 12,9300 | 0,9980 | 3,52x | Denmark | 6,3163 | 0,9510 | 1,00x |
| | 19,4130 | 1,0000 | 5,28x | | 14,5320 | 0,9409 | 2,30x |
| | 20,0870 | 1,0000 | 5,46x | Spain | 4,3626 | 0,8327 | 1,00x |
| Denmark | 5,8088 | 0,9931 | 1,00x | | 9,4489 | 0,9797 | 2,17x |
| | 8,9331 | 0,9850 | 1,54x | France | 7,5959 | 0,9997 | 1,00x |
| Spain | 4,8858 | 0,9421 | 1,00x | | 10,1350 | 0,9988 | 1,33x |
| | 6,5569 | 0,9911 | 1,34x | | 11,0550 | 0,9987 | 1,46x |
| | 9,7586 | 0,9943 | 2,00x | | 13,0830 | 0,9980 | 1,72x |
| | 13,2830 | 0,9911 | 2,72x | | 14,4010 | 0,9996 | 1,90x |
| France | 3,0480 | 0,9888 | 1,00x | | 16,4710 | 0,9900 | 2,17x |
| | 4,5865 | 0,9899 | 1,50x | Greece | 5,1014 | 0,9888 | 1,00x |
| | 6,6430 | 0,9959 | 2,18x | | 9,6822 | 0,9992 | 1,90x |
| | 7,9141 | 1,0000 | 2,60x | | 13,4200 | 0,9930 | 2,63x |
| | 9,8211 | 0,9904 | 3,22x | Hungary | 10,9720 | 0,9837 | 1,00x |
| Hungary | 5,0239 | 0,9741 | 1,00x | Italy | 5,1564 | 0,9927 | 1,00x |
| | 6,4873 | 0,9767 | 1,29x | | 7,2243 | 0,9956 | 1,40x |
| Italy | 4,0420 | 0,9930 | 1,00x | | 9,3035 | 0,9971 | 1,80x |
| | 5,1043 | 0,9996 | 1,26x | | 14,6590 | 0,9995 | 2,84x |
| | 5,9490 | 0,9988 | 1,47x | Netherlands | 10,4900 | 0,9640 | 1,00x |
| | 7,1990 | 0,9987 | 1,78x | | 14,7870 | 0,8630 | 1,41x |
| | 8,4739 | 0,9912 | 2,10x | Poland | 10,3110 | 0,9966 | 1,00x |
| | 10,5490 | 0,9996 | 2,61x | | 11,5460 | 0,9910 | 1,12x |
| | 14,6560 | 0,9999 | 3,63x | Portugal | 5,4268 | 0,9984 | 1,00x |
| Netherlands | 7,7925 | 0,7442 | 1,00x | | 8,1392 | 0,9817 | 1,50x |
| Poland | 5,6169 | 0,9923 | 1,00x | | 10,8560 | 0,9916 | 2,00x |
| | 7,0481 | 0,9887 | 1,25x | Romania | 9,6395 | 0,9954 | 1,00x |
| | 10,3320 | 0,9894 | 1,84x | Russia | 10,6060 | 0,9982 | 1,00x |
| Portugal | 2,3511 | 0,9707 | 1,00x | | 11,5220 | 0,9992 | 1,09x |
| | 5,4340 | 0,9969 | 2,31x | | | | |
| | 10,8060 | 0,9846 | 4,60x | | | | |
| Romania | 5,5193 | 0,9999 | 1,00x | | | | |
| | 6,1165 | 0,9998 | 1,11x | | | | |
| Russia | 5,4036 | 0,9967 | 1,00x | | | | |
| | 6,9497 | 0,9976 | 1,29x | | | | |

**Table 11: Comprehensive list of X/R relations for lines at 220 and 400 kV**

### 2.3.3. Capacitive Susceptance

Finally, regarding line capacity, that is capacitive susceptance, not transmission-line capacity, the same distinction as has been made as with resistance and reactance. As this parameter increases with line distance, as well as with line geometry, it should show larger capacitive susceptances for longer lines. Figure 21 and Figure 22 illustrate this information as do Table 12 and Table 13 in greater detail.

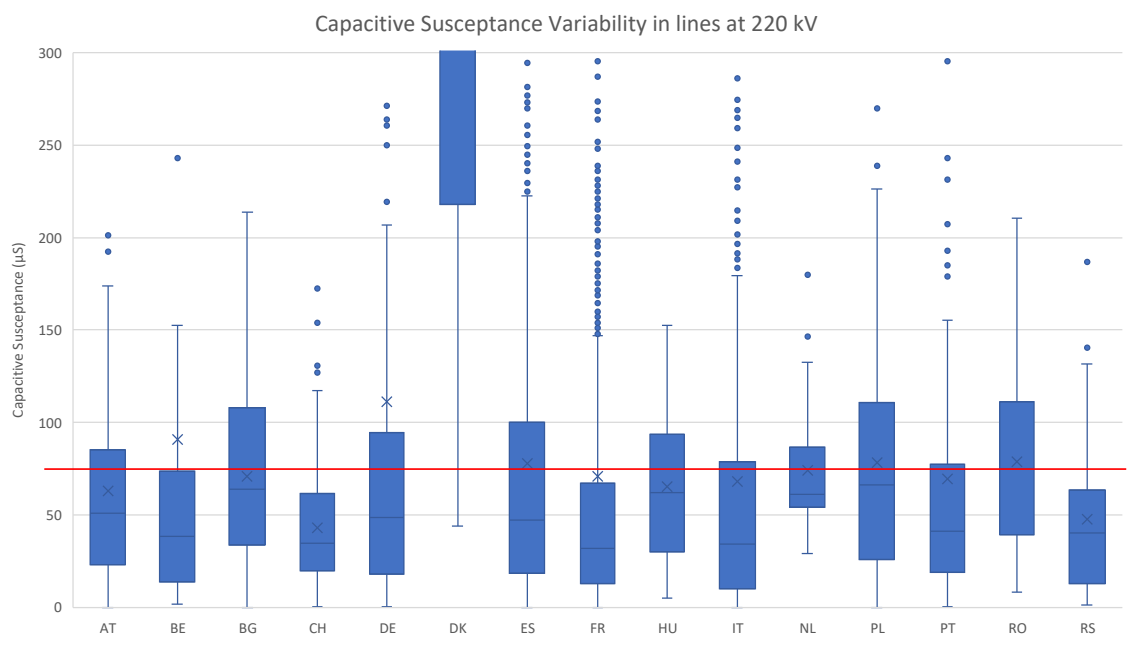



**Figure 21: Capacitive Susceptance data summary per country for lines at 220 kV**

This graph is quite warped due to the information provided by Denmark. Denmark provides information aside from that available through ENTSO-E and in that cohort, the average capacitive susceptance is 1200 µS, validating the information available in ENTSO-E. This big deviation is probably due to the fact that there are only 11 lines at this voltage level, which might have anomalous characteristics that cannot be smoothed out by a larger quantity of data.

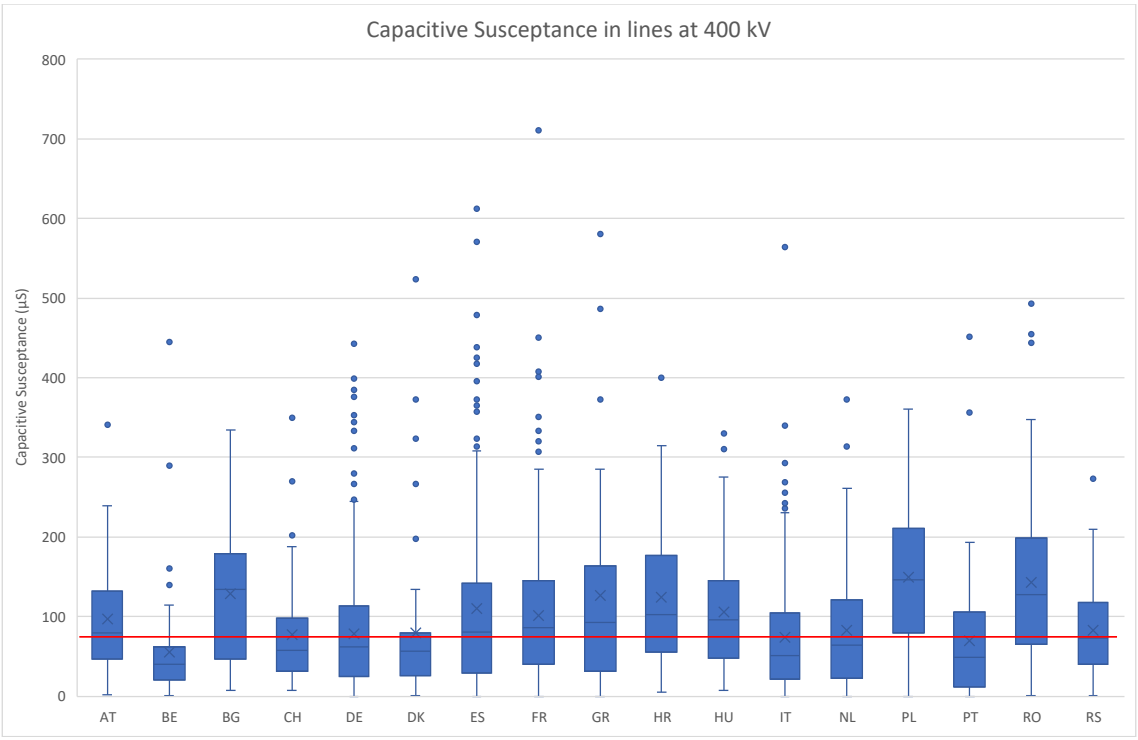



Figure 22: Capacitive Susceptance data summary per country for lines at 400 kV

| Country | N. Lines | B/2 Max | B/2 Min | B/2 avg | $\sigma$ B/2 | Median B/2 | B/2 25th Per | B/2 75th Per |
|---|---|---|---|---|---|---|---|---|
| Austria | 114 | 490,878 | 0,000 | 61,698 | 62,483 | 50,858 | 21,712 | 84,677 |
| Belgium | 37 | 811,459 | 0,000 | 88,413 | 181,373 | 36,715 | 12,975 | 73,192 |
| Bulgaria | 59 | 213,541 | 0,000 | 70,763 | 48,922 | 63,864 | 33,502 | 106,018 |
| Croatia | 31 | 372,118 | 4,070 | 61,285 | 69,699 | 42,934 | 24,360 | 71,803 |
| Denmark | 11 | 2215,721 | 0,000 | 860,632 | 790,188 | 1061,859 | 65,601 | 1365,172 |
| France | 1590 | 2452,004 | 0,000 | 69,844 | 154,908 | 31,002 | 12,004 | 66,002 |
| Germany | 503 | 2916,001 | 0,000 | 106,226 | 342,244 | 43,981 | 15,100 | 91,131 |
| Greece | - | - | - | - | - | - | - | - |
| Hungary | 30 | 152,676 | 4,731 | 65,029 | 44,270 | 62,133 | 33,306 | 92,033 |
| Italy | 493 | 1724,731 | 0,000 | 67,532 | 133,282 | 33,895 | 9,556 | 77,428 |
| Netherlands | 30 | 179,969 | 0,000 | 68,914 | 40,359 | 59,990 | 53,573 | 85,062 |
| Polland | 150 | 325,282 | 0,000 | 77,390 | 65,813 | 65,217 | 25,881 | 107,748 |
| Portugal | 179 | 784,139 | 0,000 | 67,581 | 96,678 | 39,244 | 16,472 | 75,160 |
| Romania | 90 | 210,599 | 0,000 | 77,985 | 47,103 | 74,690 | 38,846 | 110,142 |
| Russia | 75 | 188,781 | 0,000 | 43,329 | 42,069 | 39,814 | 10,852 | 61,787 |
| Spain | 851 | 1334,184 | 0,000 | 75,942 | 96,733 | 44,514 | 17,562 | 98,874 |
| Switzerland | 201 | 172,645 | 0,403 | 43,096 | 31,669 | 34,545 | 19,948 | 61,374 |
| **Weighted average** | | | | **74,955** | **113,768** | **42,484** | **16,047** | **83,575** |

**Table 12: Capacitive Susceptance data summary per country for lines at 220 kV**

| Country | N. Lines | B/2 Max | B/2 Min | B/2 avg | σ B/2 | Median B/2 | B/2 25th Per | B/2 75th Per |
|---|---|---|---|---|---|---|---|---|
| Austria | 62 | 343,947 | 2,031 | 96,849 | 77,733 | 79,325 | 46,872 | 128,365 |
| Belgium | 79 | 444,278 | 0,441 | 55,359 | 63,632 | 40,000 | 20,431 | 62,381 |
| Bulgaria | 46 | 334,219 | 8,062 | 129,176 | 87,634 | 134,663 | 55,521 | 175,555 |
| Croatia | 26 | 399,456 | 5,888 | 124,572 | 93,878 | 103,042 | 62,369 | 171,317 |
| Denmark | 72 | 1265,919 | 0,000 | 87,594 | 169,127 | 51,019 | 16,318 | 74,679 |
| France | 458 | 710,000 | 0,000 | 98,338 | 85,239 | 84,658 | 35,991 | 141,875 |
| Germany | 1226 | 3062,996 | 0,000 | 80,678 | 146,293 | 57,655 | 20,869 | 110,924 |
| Greece | 114 | 580,272 | 0,000 | 116,665 | 120,964 | 86,681 | 26,362 | 164,219 |
| Hungary | 57 | 329,803 | 7,872 | 106,353 | 69,214 | 95,606 | 48,381 | 139,203 |
| Italy | 373 | 1511,157 | 0,000 | 79,747 | 128,602 | 48,138 | 18,399 | 100,969 |
| Netherlands | 83 | 372,281 | 0,000 | 77,388 | 80,465 | 62,828 | 16,499 | 118,741 |
| Polland | 105 | 360,500 | 0,009 | 149,649 | 86,599 | 146,700 | 84,419 | 209,681 |
| Portugal | 97 | 451,144 | 0,266 | 70,028 | 78,701 | 49,337 | 11,734 | 102,344 |
| Romania | 80 | 492,950 | 0,891 | 142,636 | 102,734 | 127,250 | 66,206 | 198,229 |
| Russia | 53 | 273,000 | 0,000 | 80,203 | 63,365 | 71,850 | 33,647 | 107,850 |
| Spain | 346 | 611,713 | 0,000 | 109,954 | 108,688 | 80,166 | 28,794 | 141,834 |
| Switzerland | 74 | 350,000 | 0,000 | 76,031 | 69,076 | 57,350 | 31,812 | 96,854 |
| **Grand Total** | | | | **91,669** | **95,997** | **70,052** | **28,449** | **124,052** |

**Table 13: Capacitive Susceptance data summary per country for lines at 400 kV**

At the 400-kV level, lines in Germany, Denmark and Italy show very high maximum capacitive susceptance values. This might be due to these countries having more lines in a multiple line per circuit configuration, resulting in higher capacitive values.

It is interesting to observe the relation between X and B for the lines in the different countries. The result is there are a breadth of different relations, similar to that of R and X.

No clear global pattern can be discerned linking thermal rating and capacitive susceptance from Figure 23 and Figure 24.

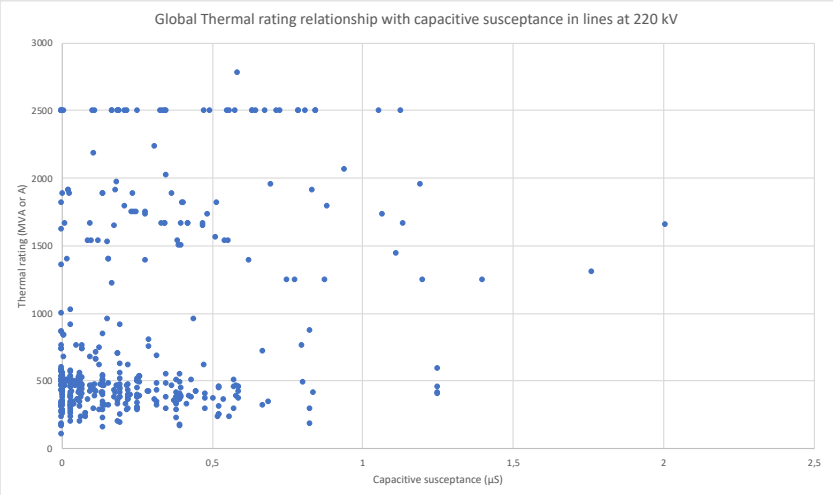



**Figure 23: Thermal rating relationship with capacitive susceptance in lines at 220 kV**

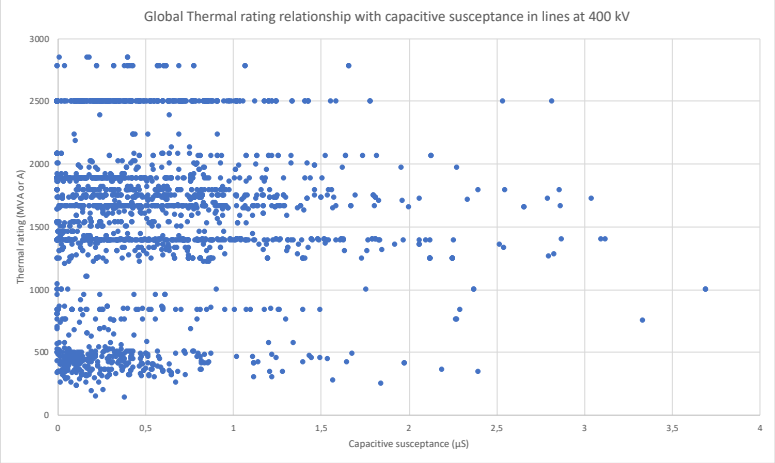



**Figure 24: Thermal rating relationship with capacitive susceptance in lines at 400 kV**

Finally, in the ENTSO-E data of the TYNDP of 2014, information regarding the number of circuits of each line was published. Table 14, Figure 25 and Figure 26 summarize this information and show how resistance falls dramatically with number of circuits and thermal rating increases as well. Linking this to distance data will be helpful as it might serve as a basis for assigning thermal ratings to lines in synthetic networks.

| Voltages | No. of circuits | No. of lines | Average TR(MVA) | Average TR/circuit | Average R (ohms) | Average R/circuit |
|---|---|---|---|---|---|---|
| **220** | | **4288** | **1223** | | **3,140** | |
| | 1 | 3893 | 1071 | 1071 | 3,388 | 3,388 |
| | 2 | 388 | 2477 | 1238 | 0,704 | 1,408 |
| | >3 | 1 | 1800 | 450 | 0,292 | 1,169 |
| **400** | | **1262** | **2248** | | **2,747** | |
| | 1 | 1096 | 1975 | 1975 | 3,043 | 3,043 |
| | 2 | 161 | 4134 | 2067 | 0,795 | 1,591 |
| 3 | >3 | 5 | 6150 | 2050 | 0,813 | 2,439 |
| **Weighted Average** | | **5550** | **1464** | | **3,050** | |

**Table 14: Summary of number of circuits and their corresponding resistance and thermal rating**

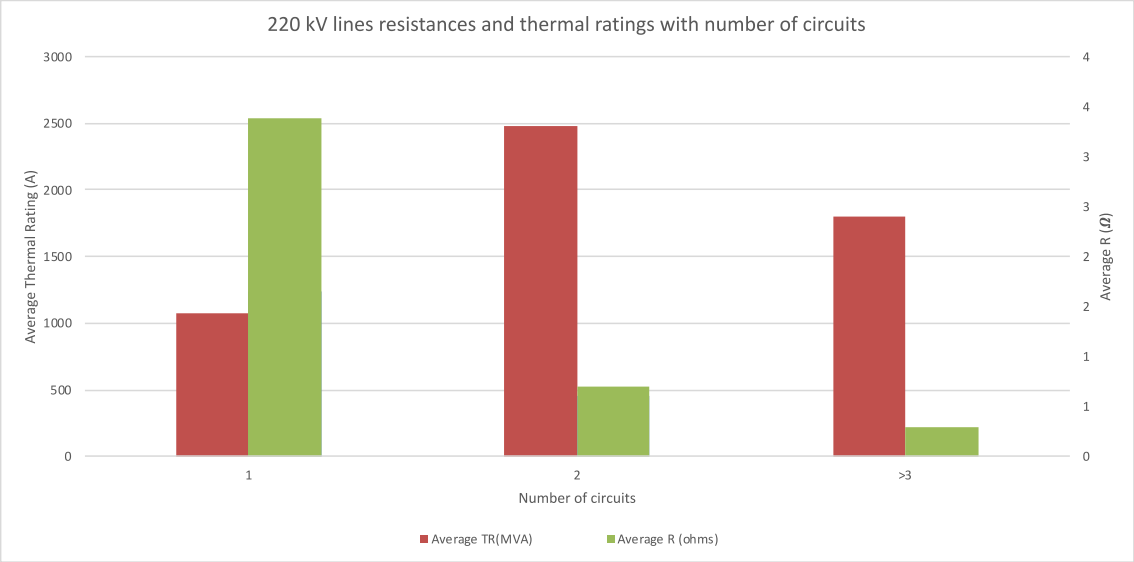



**Figure 25: Resistance and thermal rating relation with number of circuits in lines at 220 kV**

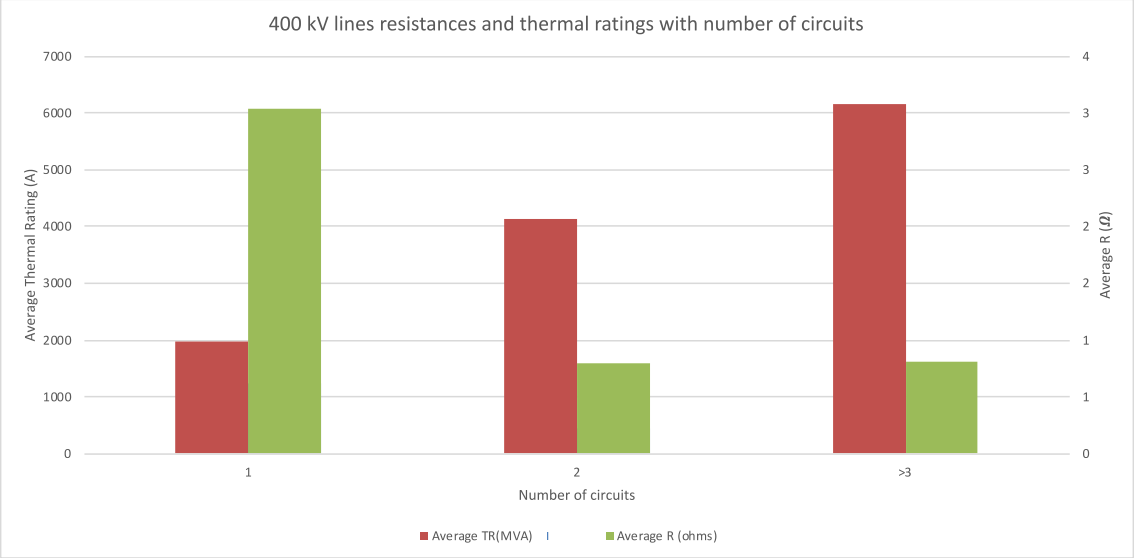



**Figure 26: Resistance and thermal rating relation with number of circuits in lines at 400 kV**

## 2.4. Analysis of data provided by individual TSO's

Aside from ENTSO-E, some TSO's provide power-network data which is understood to be more up to date. This is the case of France, Belgium and Denmark. For this data, it is interesting to bring the distance information available. This data can shed more light as to whether parameters such as resistance, reactance and capacitive susceptance really are in any way proportional with distance. Simply comparing the data and its variability with respect to the ENTSO-E data could serve a validating point for said data.

### 2.1.1. France

Firstly, a simple check of coherence with the ENTSO-E data is helpful as a means of validating the previous analysis. Table 15 summarise the resistance data, as well as the reactance and capacitance data from RTE and ENTSO-E. It shows slight deviations in all categories, but the order of magnitude matches in all but B/2, where almost all results are about ten times different. This could be due to the units used in both cases, as well as the type of information provided, but it seems unlikely that one is Farads and the other Siemens as the difference would be much larger, by a factor near 50*$\pi$. This factor is calculated in Equation 11.

| Source | Voltage | No. of Lines | RMax (ohms) | RMin (ohms) | Ravg (ohms) | $\sigma$ R (ohms) | Median R | R 25th Perc. | R 75th Perc. |
|---|---|---|---|---|---|---|---|---|---|
| RTE | 220kV | 541 | 14,456 | 0,010 | 2,233 | 2,106 | 1,551 | 0,820 | 2,766 |
| | 400kV | 285 | 9,503 | 0,147 | 1,722 | 1,274 | 1,459 | 0,805 | 2,154 |
| ENTSO-E | 220kV | 1590 | 14,456 | 0,000 | 1,219 | 1,606 | 0,640 | 0,186 | 1,615 |
| | 400 kV | 458 | 9,499 | 0,000 | 1,253 | 1,201 | 0,948 | 0,419 | 1,765 |
| | | No. of Lines | XMax (ohms) | XMin (ohms) | Xavg (ohms) | $\sigma$ X (ohms) | Median X | X 25th Perc. | X 75th Perc. |
| RTE | 220kV | 541 | 51,773 | 0,010 | 12,126 | 9,002 | 9,744 | 5,541 | 16,903 |
| | 400kV | 285 | 73,668 | 2,356 | 19,706 | 12,963 | 17,309 | 9,773 | 26,625 |
| ENTSO-E | 220kV | 1590 | 56,100 | 0,048 | 6,699 | 7,727 | 4,162 | 0,978 | 9,522 |
| | 400 kV | 458 | 73,670 | 0,102 | 14,512 | 12,676 | 11,667 | 5,364 | 21,245 |
| | | No. of Lines | B/2 Max | B/2 Min | B/2 avg | $\sigma$ B/2 | Median B/2 | B/2 25th Perc | B/2 75th Perc. |
| RTE | 220kV | 543 | 2451,000 | 0,000 | 59,214 | 114,108 | 41,838 | 25,246 | 67,998 |
| | 400kV | 286 | 450,366 | 0,000 | 126,792 | 81,755 | 107,936 | 65,198 | 165,893 |
| ENTSO-E | 220kV | 1590 | 2452,004 | 0,000 | 69,844 | 154,908 | 31,002 | 12,004 | 66,002 |
| | 400kV | 458 | 710,000 | 0,000 | 98,338 | 85,239 | 84,658 | 84,658 | 84,658 |

**Table 15: Resistance comparison data between RTE and ENTSO-E for lines in France**

$$\frac{B}{2} = \frac{\omega * C}{2} = \frac{2 * \pi * f * C}{2} = \pi * f * C = 50\pi * C \approx 157 * C$$

**Equation 11: Conversion between capacity in farads and capacitive susceptance in Siemens**

Following this, the ratio of reactance to resistance was previously analysed in an effort to distinguish different line types, be it their geometric properties or any relation that can be extracted from them when assigning values in a synthetic network. In Figure 27 and Figure 28, this relations from the data provided by RTE can be observed.

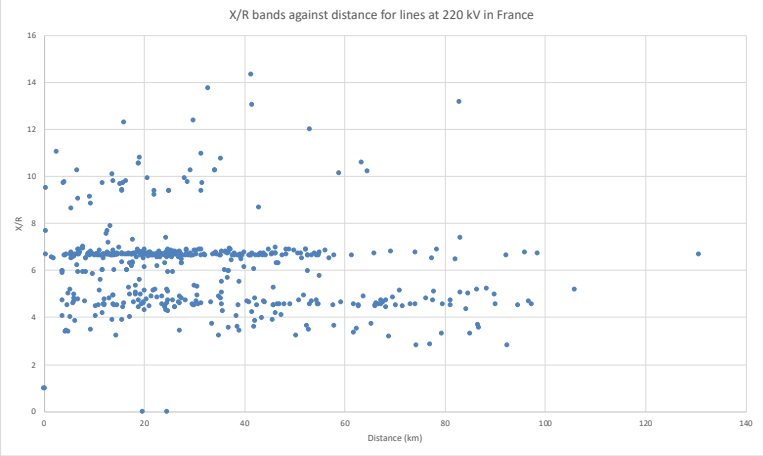



**Figure 27: X/R ratio with respect to line distance for lines at 220 kV in France**

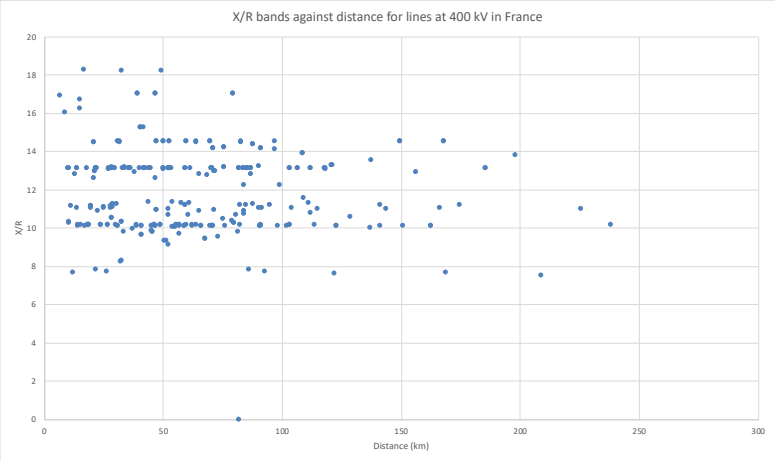



**Figure 28: X/R ratio with respect to line distance for lines at 400 kV in France**

In the data provided by ENTSO-E, the relations observed are documented in Table 11 show very similar results, with relations at 220 kV range from 3 to 9,8 and relations at 400 kV range from 7,6 to 16,5.

Coming to the most important piece of information contained within the data published by RTE, the distance component and its relations to the different electrical characteristics of lines will be illustrated. Figure 29 and Figure 30 illustrate the relationship between line resistance and their length. It is very clear that there are four main types of lines at 220 kV and three at 400 kV. This might be due to the configuration of the line or it might have to do with other parameters such as number of circuits, however, RTE treats several circuits for the same line as different individual lines.

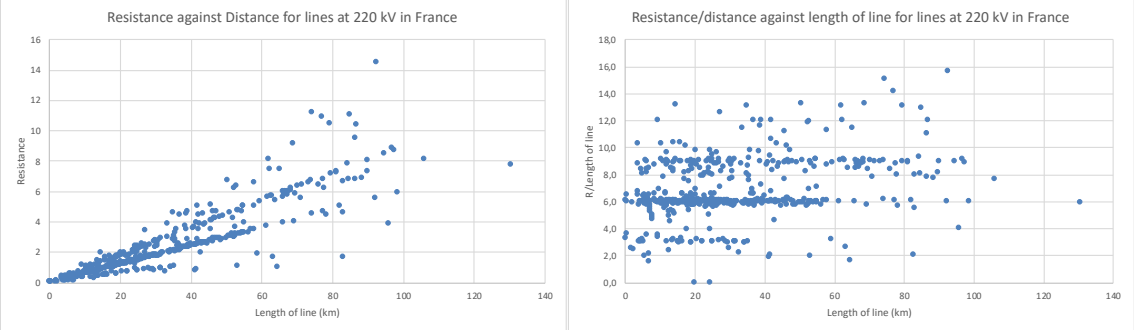



**Figure 29: Relation summary between R and distance in lines at 220 kV in France**

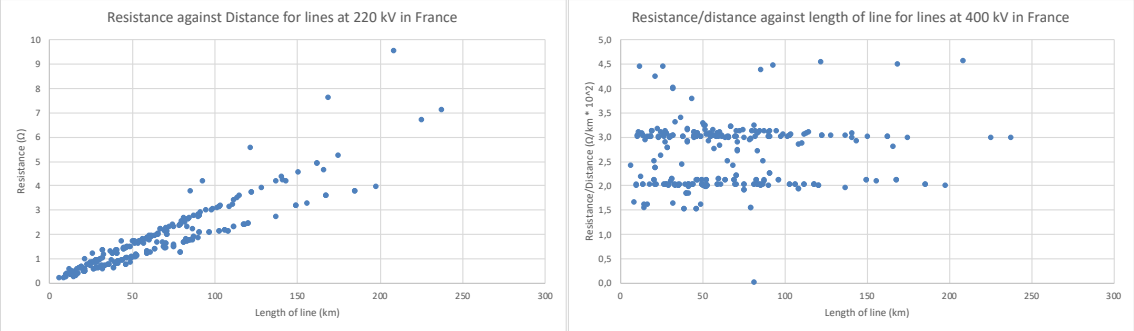



**Figure 30: Relation summary between R and distance in lines at 400 kV in France**

From Figure 29 and Figure 30 it is clear that the distances covered by 220 kV lines has an upper limit at around 100 km, whereas lines at 400 kV can cover distances up to 250 km.

Following on to impedances and their relation to distance, Figure 31 and Figure 32 show a similar trend to that of resistance, increasing linearly with distance. This is also in line with the information illustrated in Figure 27 and Figure 28, as resistance and impedance are interrelated in a series of constant relations.

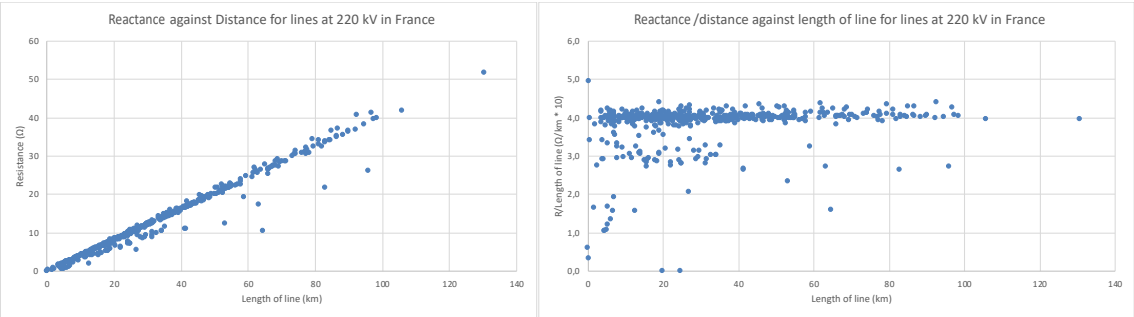



**Figure 31: Relation summary between X and distance in lines at 220 kV in France**

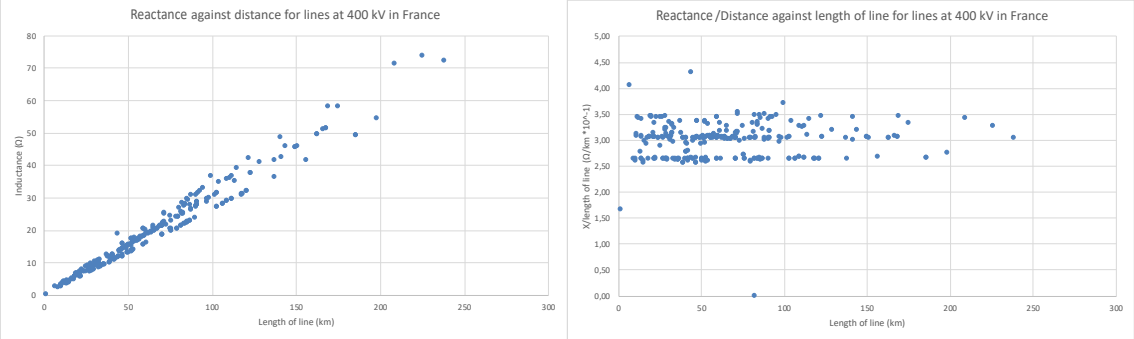



**Figure 32: Relation summary between X and distance in lines at 220 kV in France**

As explored in the data provided by ENTSO-E, the capacitive susceptance is also an electrical component that might be useful in the characterisation of lines. In that respect, Figure 33 and Figure 34 illustrate their relationship with line length. As with resistance and reactance, there are three overall trends and their relationship with distance is very clearly linear. It is interesting to highlight that there are several lines with a very high capacitive susceptance at a very short length. This might be due to the inverse logarithmic nature of the capacitance calculation, but the lines with longer distances, as can be observed in Figure 34, this does not occur.

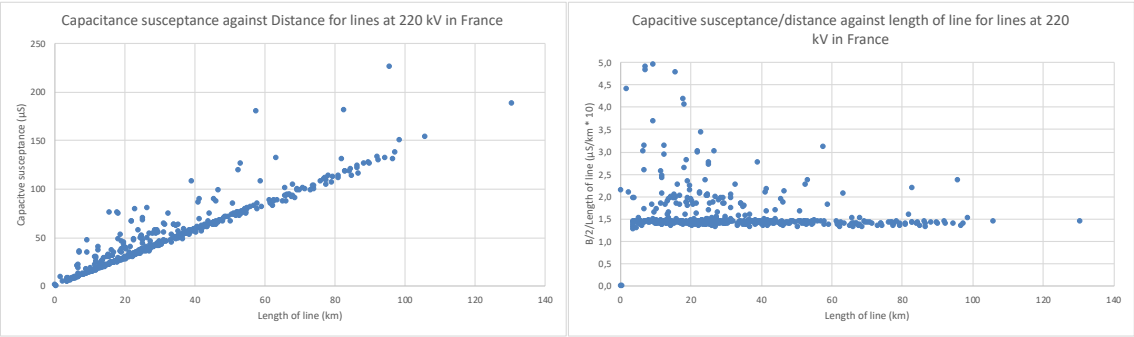



**Figure 33: Relation summary between B/2 and distance in lines at 220 kV in France**

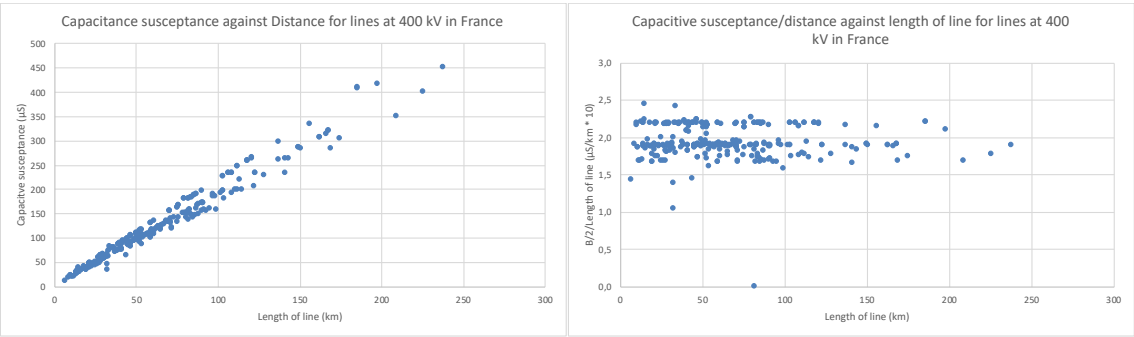



**Figure 34: Relation summary between B/2 and distance in lines at 400 kV in France**

Regarding capacitive susceptance and its link to resistance, in Figure 35 it can be observed how a certain ratio of capacitive susceptance and distance is linked to resistance and distance. This is probably due to different standard configurations of cables being

constructed with specific cable types. Figure 36 also illustrates this relationship for all lines in France, separated by voltage level.

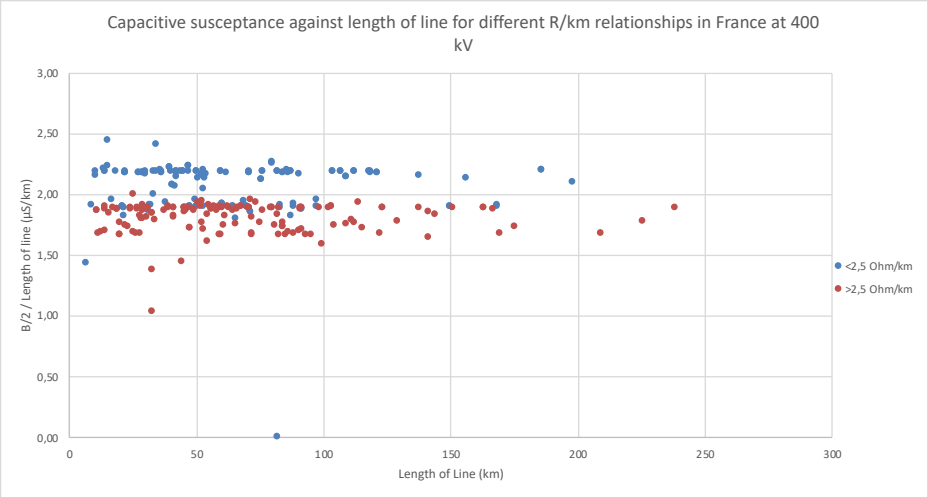



**Figure 35: Capacitive susceptance against length of line for different R/km relationships in France at 400 kV**

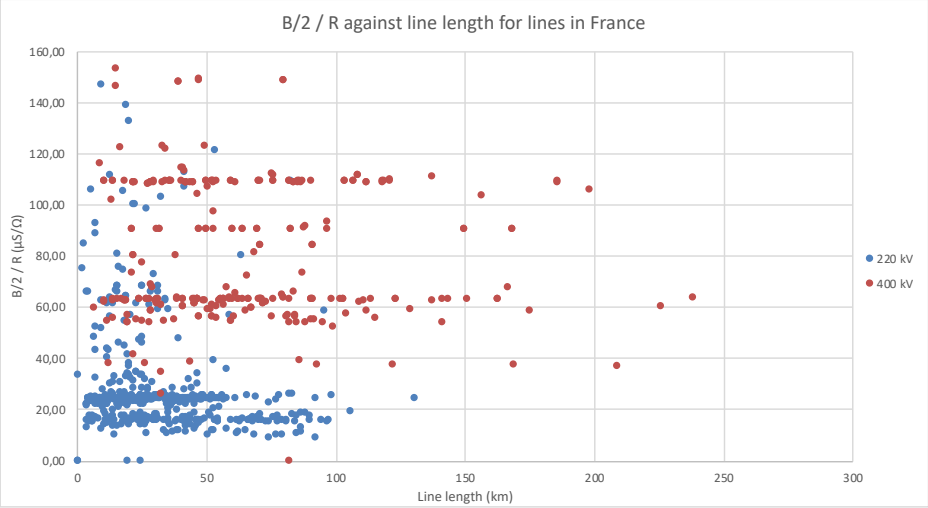



**Figure 36: B/2 / R against line length for lines per voltage level in France**

Thermal rating, or line transmission capacity is an interesting electrical component of lines, and RTE provides four values of thermal ratings. The winter scenario has been chosen as the lines can carry the highest amount of power due to lower temperatures. Figure 37 illustrates this information, and it is now clear that the relationship with distances is not linear but constant, meaning that lines are designed to carry larger amounts of power when they are longer and have higher voltages.

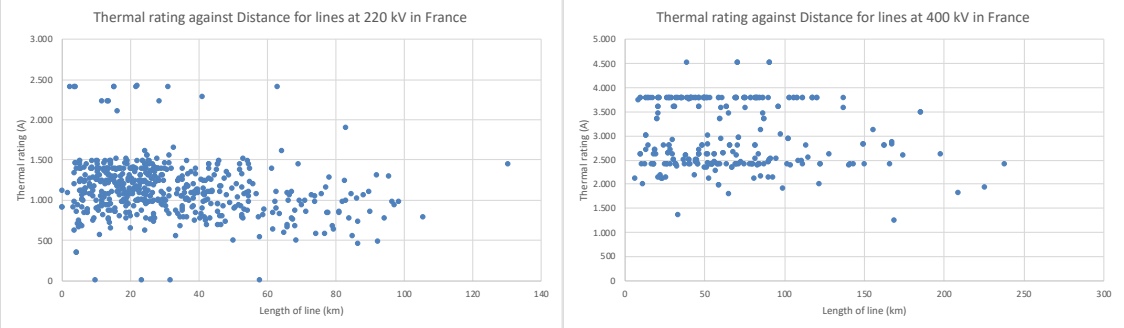



**Figure 37: Relation summary between thermal rating and distance in lines in France**

Finally, it is interesting to analyse the significance of lines having more than one circuit in terms of their length. Table 16 summarises the average length of the lines at different voltages given their number of circuits. It becomes apparent once again that lines at 400 kV are in general longer than those at 220 kV, as well as the generally larger number of lines with lower number of circuits. As stated before, RTE separates different circuits into completely different lines, meaning their electrical values are almost identical, it is their combination which results in a smaller overall resistance, for example, between two nodes.

| 220 kV | | Number lines | Max length | Min Length | Average length | Median Length | Length 25th Perc | Length 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| N. of Circuits | 3 | 18 | 45,814 | 0,465 | 17,226 | 15,295 | 7,639 | 24,467 |
| | 2 | 70 | 89,929 | 0,303 | 20,901 | 17,683 | 11,057 | 25,030 |
| | 1 | 360 | 130,633 | 1,660 | 36,310 | 30,331 | 18,936 | 49,086 |
| 400 kV | | | | | | | | |
| N. of Circuits | 5 | 1 | 39,327 | 39,327 | 39,327 | 39,327 | 39,327 | 39,327 |
| | 4 | 5 | 36,160 | 18,944 | 27,935 | 27,372 | 25,390 | 31,807 |
| | 3 | 10 | 169,194 | 21,904 | 73,081 | 62,949 | 44,405 | 86,516 |
| | 2 | 92 | 238,261 | 10,484 | 64,902 | 59,403 | 40,601 | 83,274 |
| | 1 | 73 | 225,707 | 6,805 | 76,072 | 65,573 | 34,074 | 109,145 |

**Table 16: Summary of number of circuits for lines at different voltages in France**

In Figure 38 it is interesting to remark how, in France at least, it is slightly possible to identify the clusters of thermal ratings for a given X/R ratio and a voltage. This can be very helpful when generating synthetic networks.

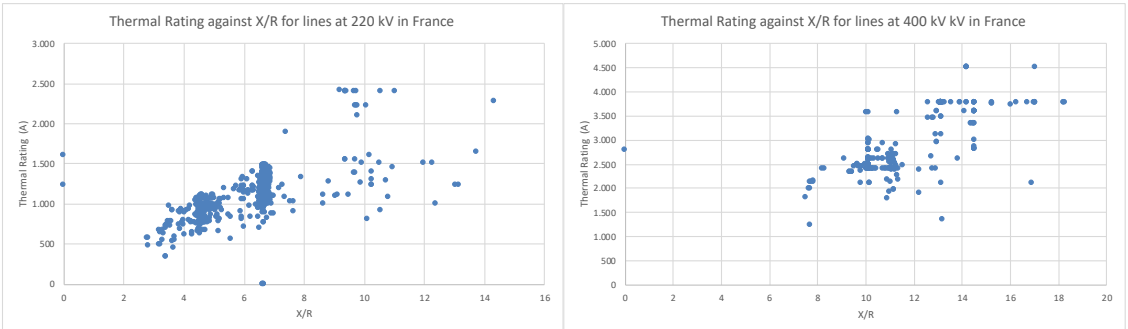



**Figure 38: Relationship between thermal rating and X/R for lines in France**

As a final note, it is interesting to verify, wherever possible, the relationship between the quoted length of a line and the straight-line distance between the geolocation of the nodes it joins. In theory, the quoted distance must be equal or longer than the straight-line distance as it is impossible to have a shorter distance than the theoretical straight line that joins the two extremes. Figure 39 shows this and confirms the assumption of quoted lines being under the spherical straight-line distance.

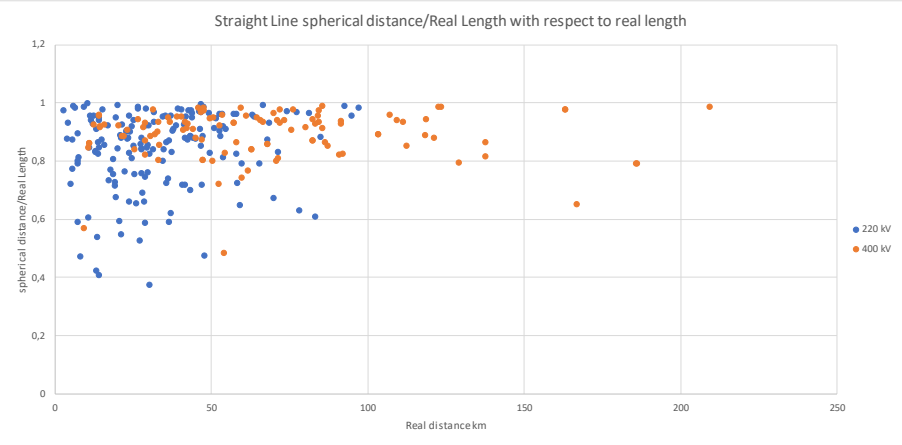



**Figure 39: Relationship between spherical and quoted distance between nodes**

### 2.1.2. Spain & Portugal

Similarly to France, information for Spain and Portugal on length of lines is available for the 400 kV network. The information available allows for the calculation of spherical straight-line length, as the geolocation of the nodes is available, but the actual length of the conductors is not available. The data regarding resistance, reactance and capacitive susceptance is the same as that available through ENTSO-E, but it is now interesting to relate the different characteristics to the length of the line they belong to. Figure 40,

Figure 41 and Figure 43 illustrate the relationship between resistance, reactance and capacitive susceptance and length respectively.

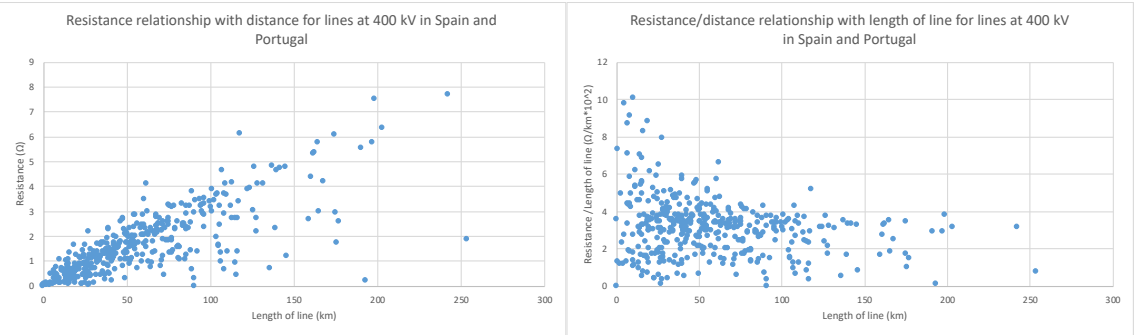



**Figure 40: Relation summary between R and distance in lines at 400 kV in Spain and Portugal**

From Figure 40 it can be seen, as well as in France, that the relationship between resistance and length of line is linear, although the patterns are not as concise as they were in France. This is most probably due to the length being calculated as the spherical straight-line distance between nodes and not the actual measured distance of said line. This will result, in general, in a ratio of resistance/ distance which is larger than it should be, due to a shorter length than in reality.

When looking at reactance in

Figure 41, a very similar outcome emerges to that of resistance. In fact, in Figure 42 it can be observed that all resistance and reactance values, when divided by each other, result in a constant value around 10 times. This relationship accentuates the linear nature with length of line of these electrical characteristics.

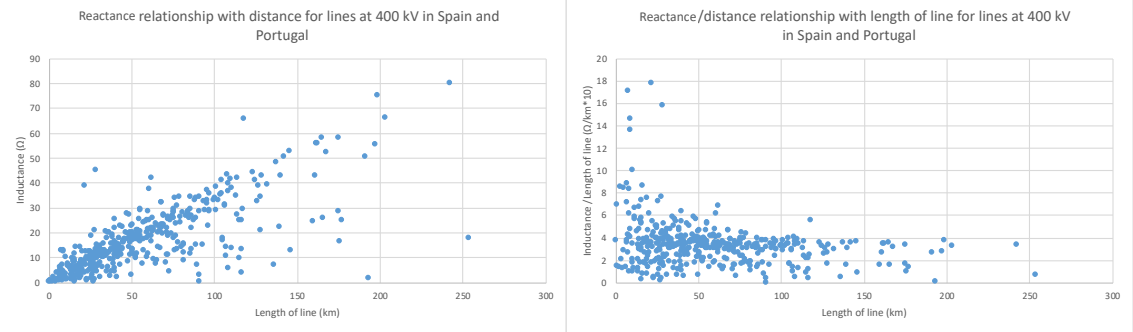



**Figure 41: Relation summary between X and distance in lines at 400 kV in Spain and Portugal**

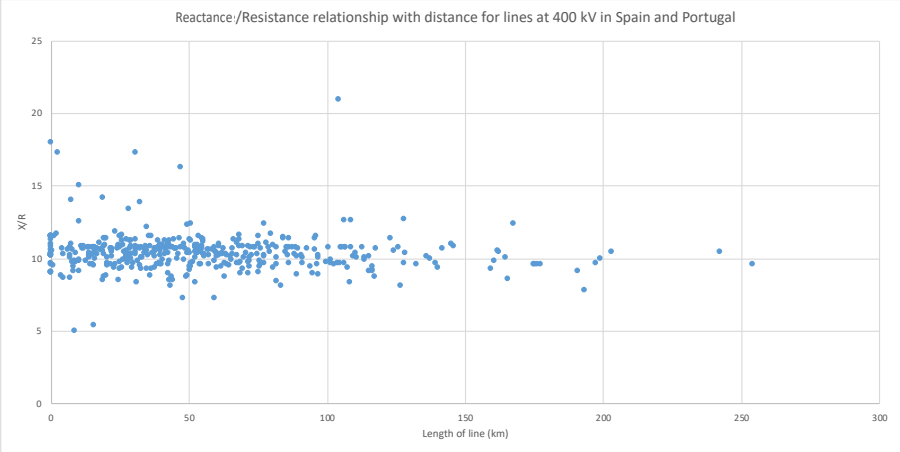



**Figure 42: X/R ratio with respect to line distance for lines at 400 kV in Spain and Portugal**

Finally, regarding capacitive susceptance, another very similar trend emerges from the data in Figure 43. A linear relationship between capacitive reactance and distance is clear around 2 µS/km.

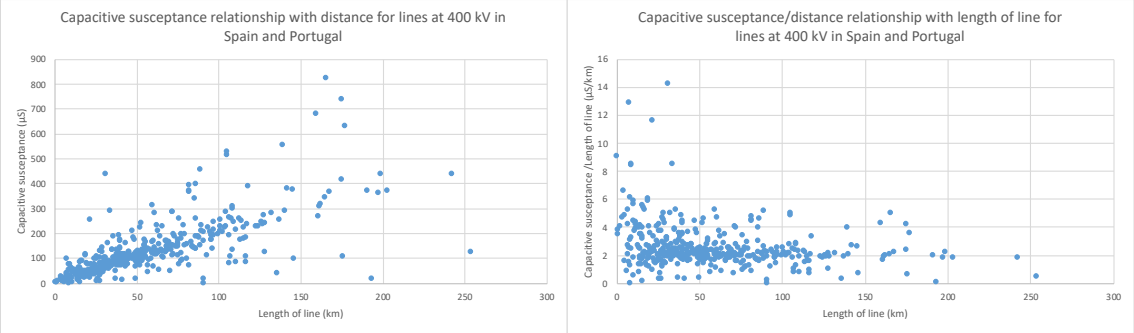



**Figure 43: Relation summary between B/2 and distance in lines at 400 kV in Spain and Portugal**

In terms of thermal rating, as can be observed in Figure 44, there are several bands like those identified in France, which in this case cover almost all distances. It does not seem very clear whether a specific thermal rating is designed in relation to distance, however, in Figure 45, X/R serves as a way of identifying a possible thermal rating for a line. The issue lies in there being only one X/R relationship in Spain and Portugal. This, again, is very useful when generating synthetic networks.

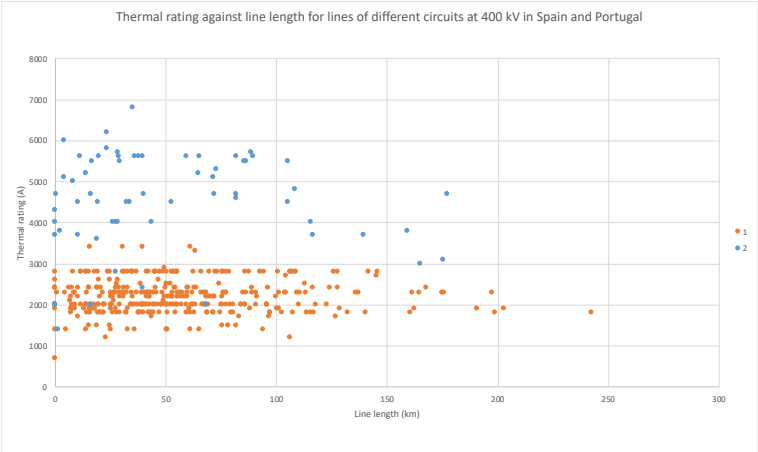



**Figure 44: Relation summary between thermal rating and distance in lines at 400 kV in Spain and Portugal**

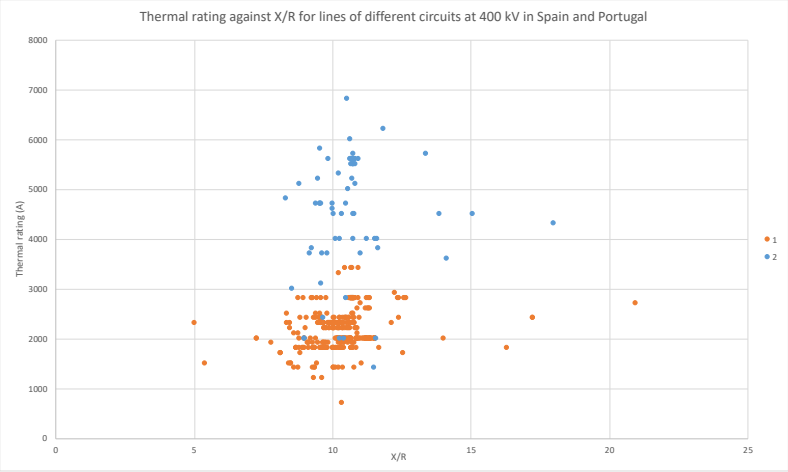



**Figure 45: Relation summary between thermal rating and X/R in lines at 400 kV in Spain and Portugal**

A final note about the information available in Spain and Portugal regarding multiple circuits per line. In this respect, unlike France where separate lines are created for different circuits of the same line, here Spain and France generate an equivalent line with the combined electrical properties of all the circuits. This results in smaller values, as can be seen in Table 17.

| 400 kV | | Number lines | Max R | Min R | Average R | Median R | R 25th Perc | R 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| N. of Circuits | 2 | 65 | 3,000 | 0,016 | 0,753 | 0,464 | 0,136 | 1,056 |
| | 1 | 374 | 7,696 | 0,000 | 1,742 | 1,440 | 0,788 | 2,364 |
| | | Number lines | Max X | Min X | Average X | Median X | X 25th Perc | X 75th Perc. |
| N. of Circuits | 2 | 65 | 32,016 | 0,144 | 7,673 | 5,008 | 1,468 | 11,136 |
| | 1 | 374 | 80,144 | 0,144 | 17,890 | 14,768 | 8,256 | 24,876 |
| | | Number lines | Max B/2 | Min B/2 | Average B/2 | Median B/2 | B/2 25th Perc | B/2 75th Perc. |
| N. of Circuits | 2 | 65 | 820,647 | 0,944 | 189,656 | 128,313 | 41,587 | 283,669 |
| | 1 | 374 | 478,537 | 0,000 | 115,384 | 99,083 | 51,287 | 149,864 |

**Table 17: Electrical characteristic values summary for different number of circuits in Spain and Portugalç**

As an illustrative way of representing the relationship between X/R and the number of circuits in a line, Figure 46 and Figure 47 show how the number of circuits don't condition the X/R of a line in Spain or Portugal.

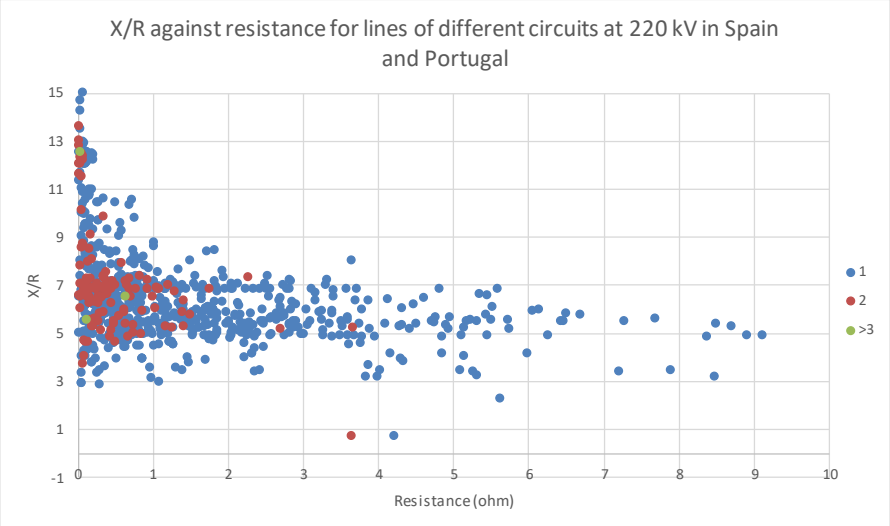



**Figure 46: X/R against resistance for lines at 220 kV in Spain and Portugal**

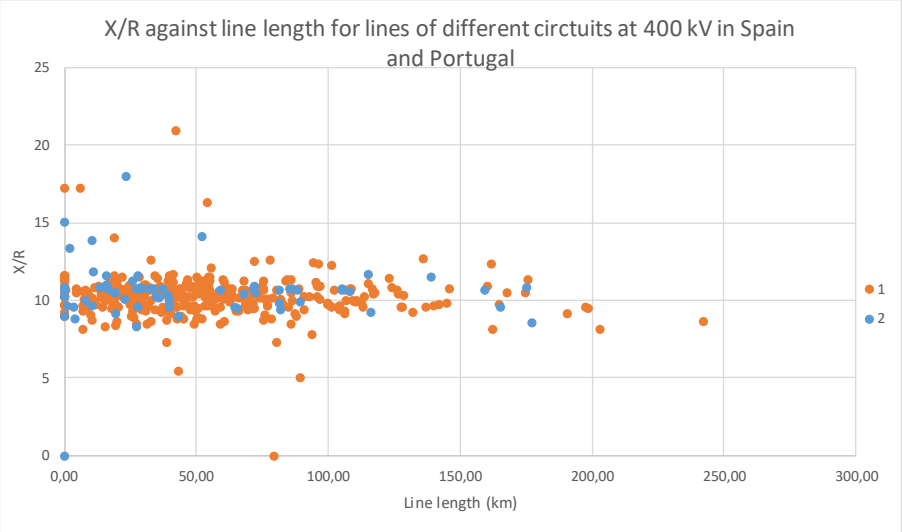



**Figure 47: X/R against length of line for lines at 400 kV in Spain and Portugal**

### 2.1.3. Belgium

Similarly to France, Spain and Portugal, Belgium provides its own information about line length, as well as separate data about resistance, reactance and capacitive susceptance. Again, as in both previous cases, the linearity between resistance and distance is conserved as can be observed in Figure 48 and Figure 49, with a clear pattern near 7,5 Ω/km*10-2 for lines at 220 kV and near 3 Ω/km*10-2 for lines at 400 kV. Although these relationships are linear, the number of lines available in this batch is quite a bit smaller than that available through ENTSO-E. In the data from the Belgium TSO Elia, only 71 lines are available, whereas in ENTSO-E there are more than 100. Nevertheless, it is very interesting to observe the degree of the linearity when the accurate distance is known.

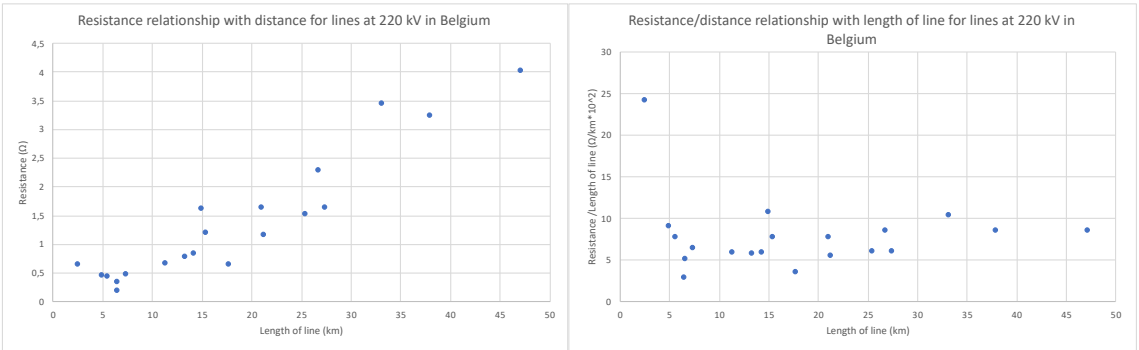



**Figure 48: Relation summary between R and distance in lines at 220 kV in Belgium**

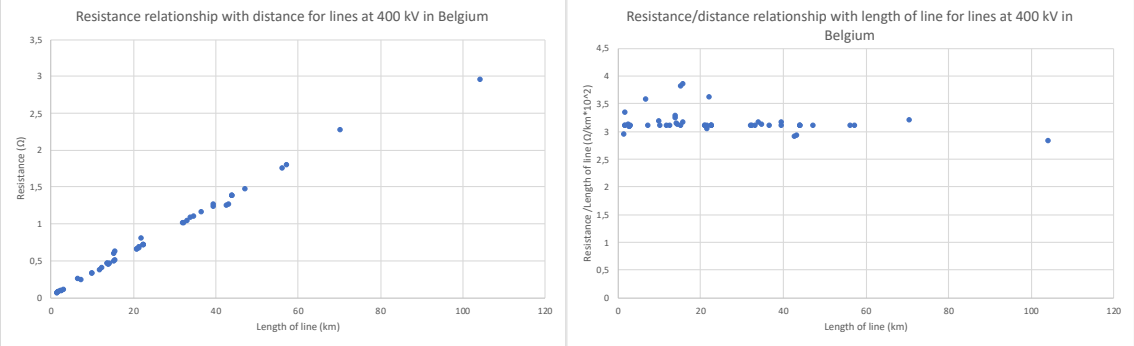



**Figure 49: Relation summary between R and distance in lines at 400 kV in Belgium**

Following on to reactance, a very similar relationship can be observed in Figure 50 and Figure 51 with reactance as with resistance. It is interesting to point out that, as with resistance, the fit of length and reactance is much greater in the lines at 400 kV than those at 220 kV. This might be due to a single type of conductor being used in lines at 400 kV whereas multiple different types are used at 220 kV.

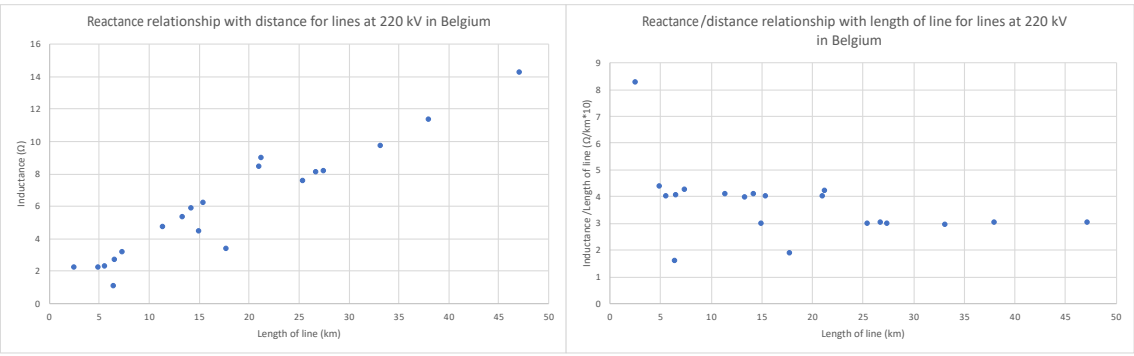



**Figure 50: Relation summary between X and distance in lines at 220 kV in Belgium**

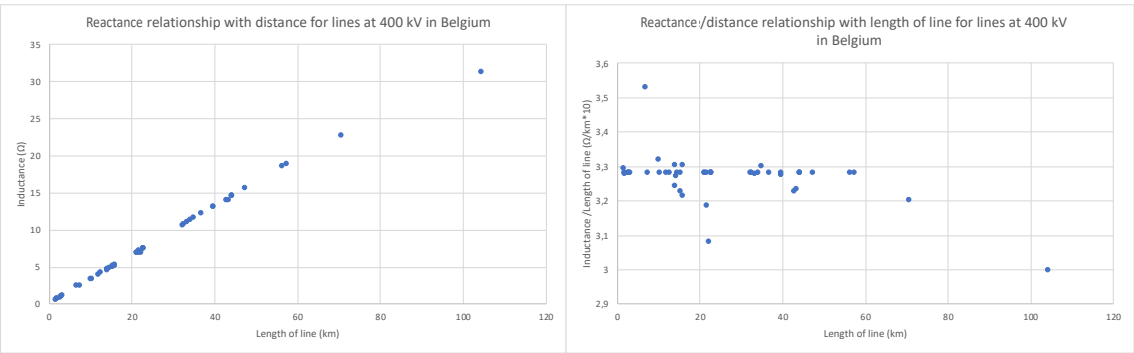



**Figure 51: Relation summary between X and distance in lines at 400 kV in Belgium**

Figure 52 illustrates the difference in fit between lines at 220 kV and those at 400 kV. In fact, there seems to be only one relation between both at 400 kV, which is in accordance with the single relationships in Figure 49 and Figure 51. At 220 kV, there isn't a clear relationship that can be extracted.

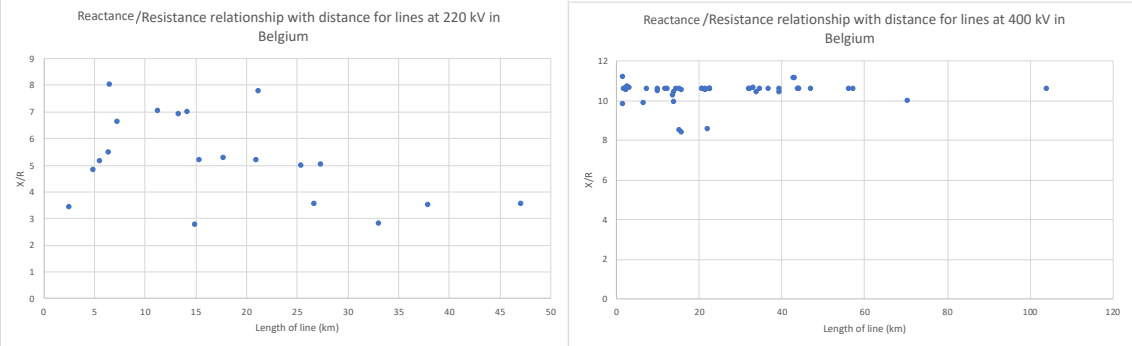



**Figure 52: X/R ratio with respect to line distance for lines in Belgium**

Finally, regarding capacitive susceptance, it can be clearly seen there is only one relationship between them and the length of the line, be that at 220 kV or 400 kV. This can be observed in Figure 53 and Figure 54. In this case, it is interesting to highlight that the two prevailing relationships are almost identical, at just under 2 $\mu$S/km, which is useful as it can be assigned to all lines within Belgium.

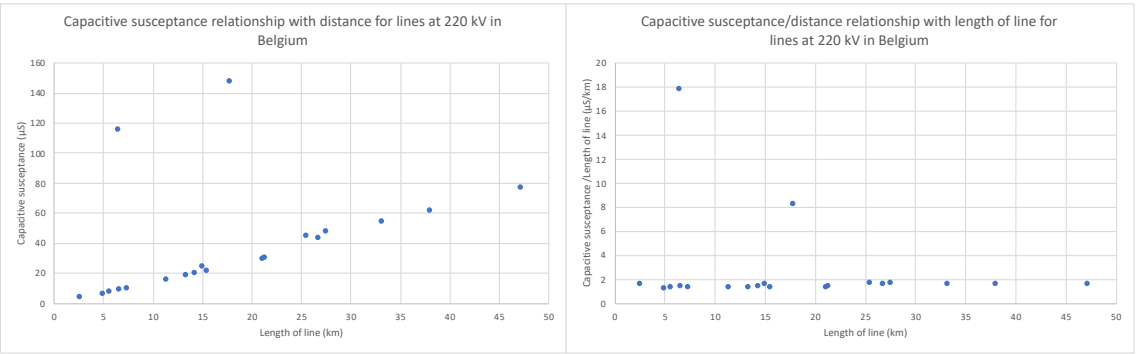



**Figure 53: Relation summary between B/2 and distance in lines at 220 kV in Belgium**

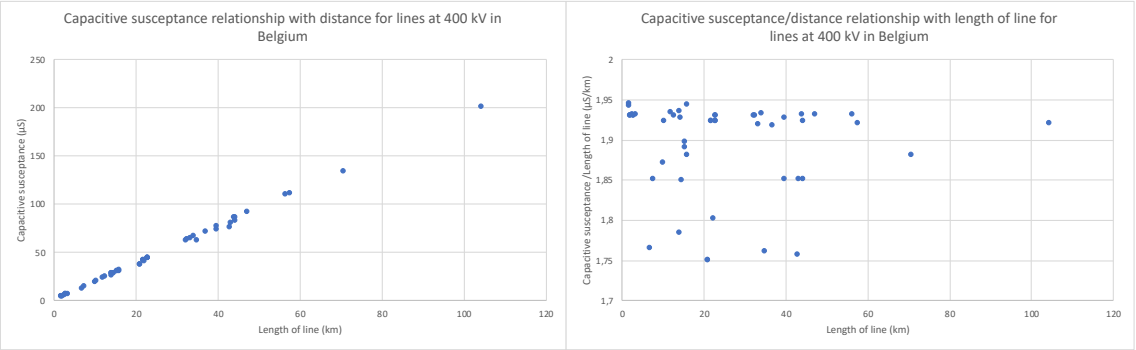



**Figure 54: Relation summary between B/2 and distance in lines at 400 kV in Belgium**

It is also interesting to highlight the relationship between thermal rating and length of the line. Figure 55 illustrates how, thermal ratings are almost constant throughout all lines at 220 kV, whereas at 400 kV, even though there are two prevailing thermal ratings, these have little relation to distance, as they both cover distances up to around 60 km, with an outlier in each case.

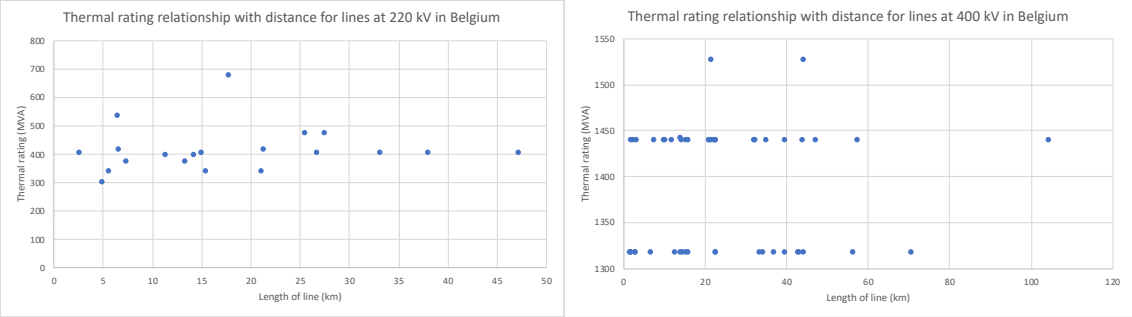



**Figure 55: Relation summary between thermal rating and distance in lines in Belgium**

In terms of relationship between thermal rating and X/R, where it might be interesting to use the latter to predict the former, it is hard to draw any conclusions, as can be observed in Figure 56.

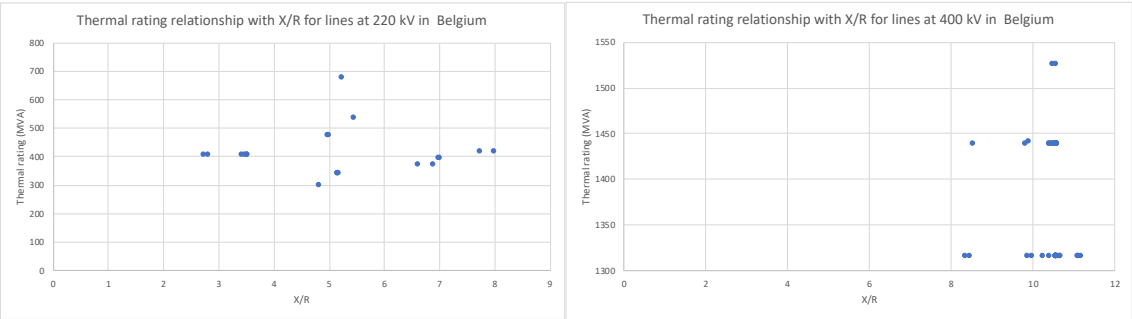



**Figure 56: Relation summary between thermal rating and X/R in lines in Belgium**

Belgium does not provide information in its data about multiple circuits on the same link between nodes. Table 18 summarises the data illustrated up to this point. It is interesting to note the similarity between the X/R multiples in practice and in theory explored in Table 26.

| Country | | | | | | |
|---|---|---|---|---|---|---|
| **France** | **Thermal Ratings (A)** | **R/Length (Ω/km*10^-2)** | **B/Length (µS/km)** | **X/R** | **Multiple** | |
| 220kV | 1000-2500 | 3 | 1,46 | 10 | 2,22x | triplex |
| | 800-1400 | 6 | 1,46 | 6,5 | 1,44x | duplex |
| | 600-1200 | 9 | 1,46 | 4,5 | 1,00x | simplex |
| 400 kV | 2500-4000 | 2 | 2,46 | 13,6 | 1,31x | duplex |
| | 2000-3000 | 3 | 1,82 | 10,41 | 1,00x | simplex |
| **Spain and Portugal** | | | | | | |
| 400 kV | 1000-6000 | 1->6 | 0,5->2 | 10 | - | |
| **Belgium** | **Thermal Rating (MVA)** | | | | | |
| 220 kV | 400 | 6,89 | 1,87 | 3->8 | - | |
| 400 kV | 1316-1526 | 3,14 | 1,89 | 10,41 | - | |

**Table 18: Resulting relationships from the data illustrated in this section**

### 2.1.4. Denmark

Denmark is a country of similar size to Belgium, and it also provides data of length of the lines within its purview. Denmark has a network with a high diversity of voltages and also a high amount of HVDC lines. As stated above, this paper will focus on the main

220 kV and 400 kV lines, even though the number of lines available at 220 kV is quite small, only 7. Figure 57 and Figure 58 show the relationship between resistance and line length. It is possible to extract a relationship at 400 kV around 2 Ω/km*$10^{-2}$ but at 220 kV the lines are too spread out to be able to conclusively say there is a clear relationship between resistance and line length at that voltage level.

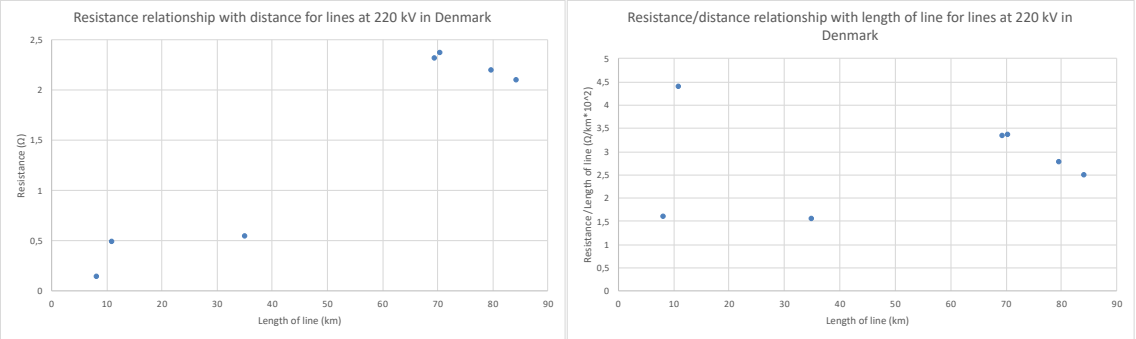



**Figure 57: Relation summary between R and distance in lines at 220 kV in Denmark**

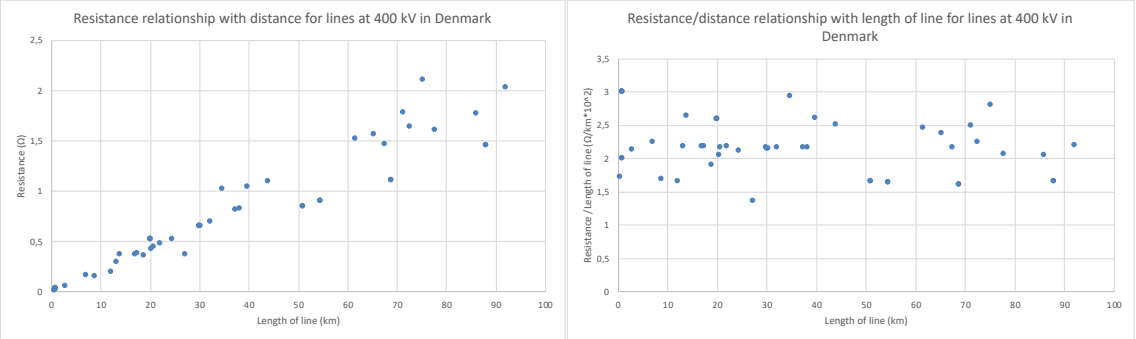



**Figure 58: Relation summary between R and distance in lines at 400 kV in Denmark**

Following on to reactance, much the same occurs, as can be observed in Figure 59 and Figure 60. Nevertheless, in the case of reactance, the lines at 220 kV align enough to be able to barely say the relationship between reactance and line length lies somewhere around 1,5 Ω/km*$10^{-2}$. The relationship for 400 kV is still a clearly visible one at around 3 Ω/km*$10^{-2}$.

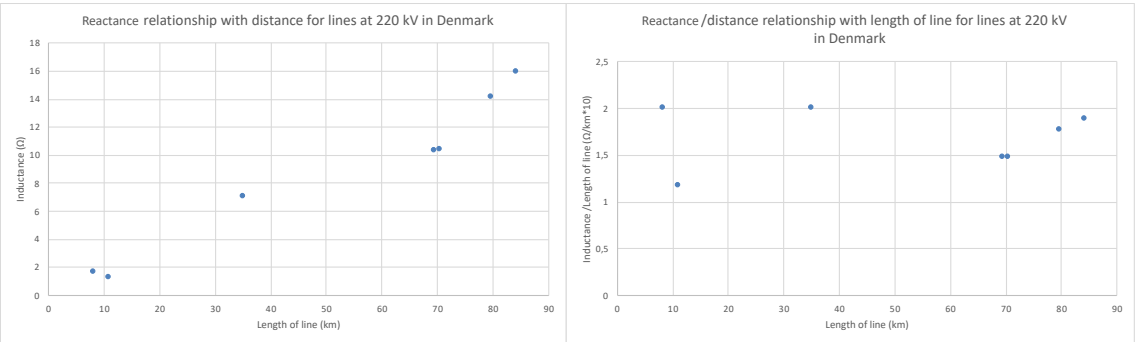



**Figure 59: Relation summary between X and distance in lines at 220 kV in Denmark**

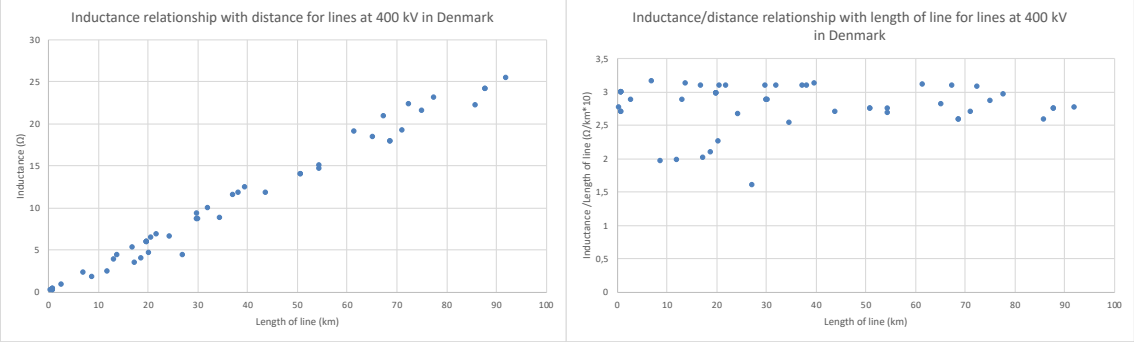



**Figure 60: Relation summary between X and distance in lines at 400 kV in Denmark**

One would hope that by correlating reactance and resistance it would be possible to identify a characteristic trait, yet as before, the ratio of X/R shows a somewhat constant ratio from 10 to 16 for all line lengths at 400 kV, yet at 220 kV the small sample of lines is too dispersing to draw any significant conclusions. Figure 61 illustrated the aforementioned points.

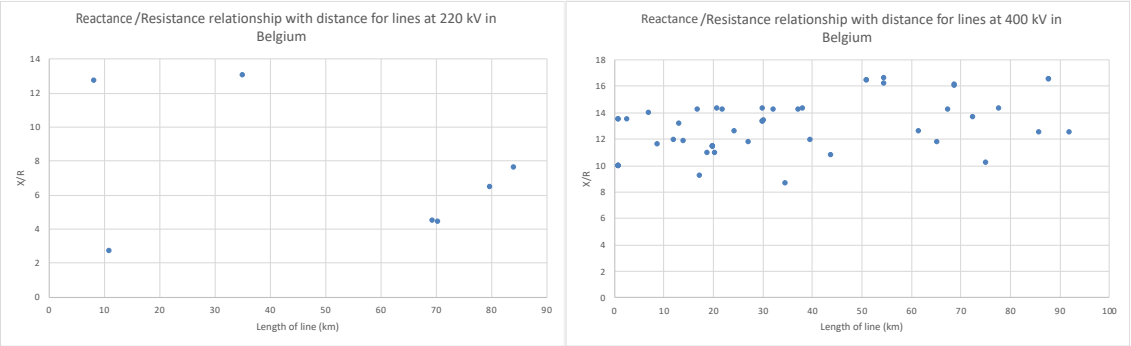



**Figure 61: X/R ratio with respect to line distance for lines in Denmark**

Finally, when threshing the capacitive susceptance data, a very similar outcome can be seen, being these results illustrated in Figure 62 and Figure 63. At 220 kV, no obvious conclusion can be drawn, but at 400 kV there seem to be two discernible relationships, around 2 μS/km*$10^{-1}$ and 5 μS/km*$10^{-1}$.

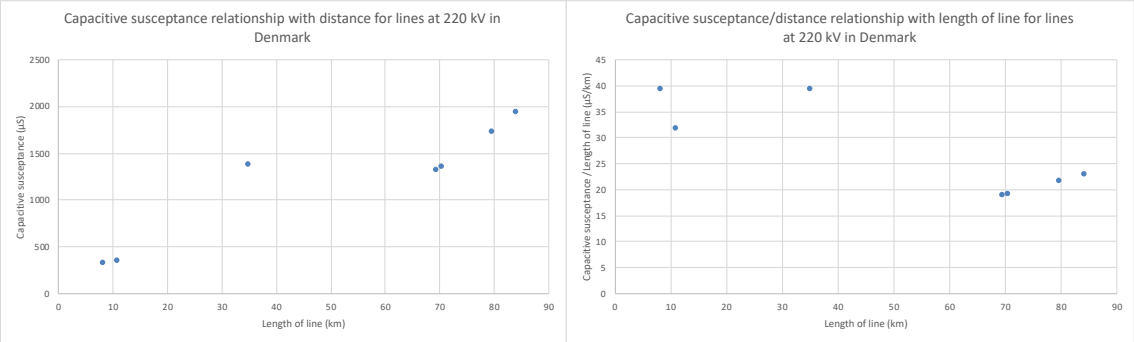



**Figure 62: Relation summary between B/2 and distance in lines at 220 kV in Denmark**

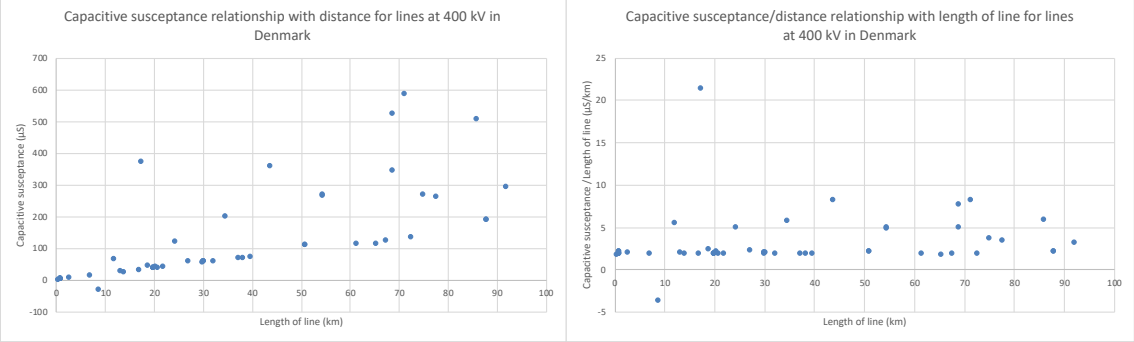



**Figure 63: Relation summary between B/2 and distance in lines at 400 kV in Denmark**

Regarding Thermal rating of the different lines, it is hard to identify relationships between it and line distance or even X/R as can be seen in Figure 64 and Figure 65, however, at 220 kV there seems to be three types of thermal ratings which coincide with different X/R values in each case. This can be observed in Figure 65.

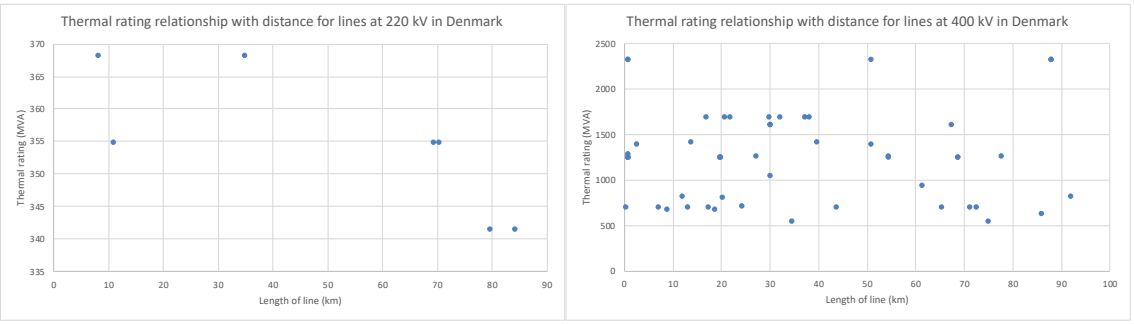



**Figure 64: Relation summary between thermal rating and distance in lines in Denmark**

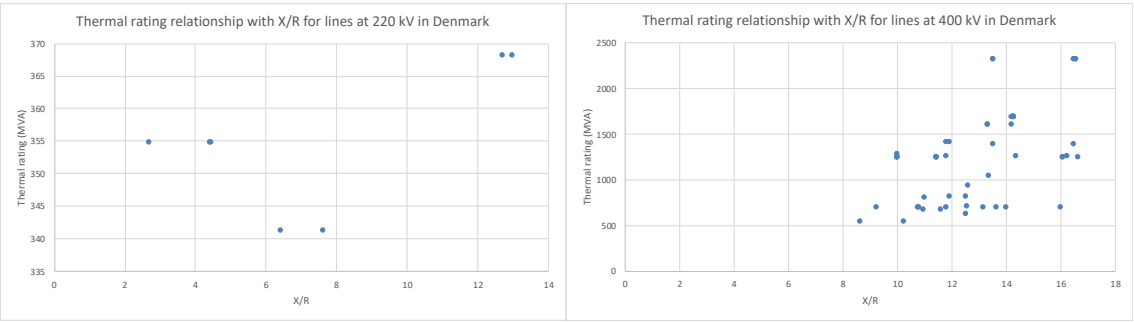



**Figure 65: Relation summary between thermal rating and X/R in lines in Denmark**

Denmark provides no information regarding different circuits connecting the same nodes.

# 3. Transformers and Shunts

ENTSO-E also provides information in its published TYNDP about transformers and shunts connected to the transmission network. It is interesting to analyse the electrical properties of these as they might have typical values that could be used when generating synthetic networks. Firstly, their characterisation will be described, followed by an analysis of the values shared by ENTSO-E.

## 3.1. Transformer Characteristic model

The data ENTSO-E publishes contains two types of transformers; transformers with two windings and transformers with three windings. On each of these windings, the information provided is its resistance, reactance and magnetising conductance. ENTSO-E shares information about 774 two-winding transformers working at the 220/400kV voltage level. The three-winding transformers usually have two voltage levels within the high voltage transmission levels, and an auxiliary winding with a voltage level below 50 kV, presumably to power auxiliary systems within the substation it serves. Figure 66 shows a simplified schematic of a transformer in a single-line diagram.

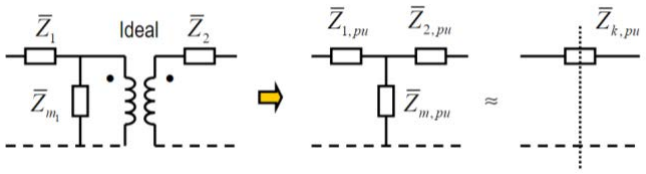



**Figure 66: Single-line diagram of three phase two winding transformer**

### 3.1.1. Two-Winding Transformer data

Table 19 summarises these characteristics for transformers with two windings by voltage levels, whereas Table 21 summarises them by nominal power. This last measure should be more useful in trying to assign standard values to transformers, possibly based on the degree of a node in graph theory. Finally, Figure 67 illustrates the data with respect to nominal power.

| Conversion | Transformers | Max R | Min R | Average R | St. Dev R | Median R | R 25th Perc | R 75th Perc. |
|---|---|---|---|---|---|---|---|---|
| 220-220 | 38 | 6,50E-03 | 0,00E+00 | 9,22E-04 | 1,38E-03 | 1,44E-04 | 5,00E-06 | 1,86E-03 |
| 220-400 | 350 | 4,40E-02 | 0,00E+00 | 4,92E-04 | 2,34E-03 | 3,32E-04 | 3,00E-04 | 4,00E-04 |
| 400-220 | 216 | 1,10E-01 | -1,87E-01 | 5,58E-04 | 1,56E-02 | 3,28E-04 | 2,08E-04 | 4,76E-04 |
| 400-400 | 170 | 5,06E-04 | 0,00E+00 | 1,34E-04 | 1,28E-04 | 1,01E-04 | 0,00E+00 | 1,94E-04 |
| **Weighted Av.** | **774** | **1,10E-01** | **-1,87E-01** | **4,53E-04** | **8,36E-03** | **2,71E-04** | **1,94E-04** | **4,48E-04** |
| | | | | | | | | |
| **Conversion** | **Transformers** | **Max X** | **Min X** | **Average X** | **St. Dev X** | **Median X** | **X 25th Perc** | **X 75th Perc.** |
| 220-220 | 38 | 1,44E-01 | 1,00E-04 | 3,36E-02 | 4,57E-02 | 1,26E-02 | 4,65E-03 | 2,78E-02 |
| 220-400 | 350 | 5,61E-02 | -1,44E-02 | 2,12E-02 | 1,62E-02 | 2,50E-02 | 1,92E-02 | 2,96E-02 |
| 400-220 | 216 | 3,21E-01 | -2,73E-01 | 2,89E-02 | 4,21E-02 | 2,63E-02 | 2,00E-02 | 2,97E-02 |
| 400-400 | 170 | 5,37E-02 | 1,00E-06 | 2,36E-02 | 1,70E-02 | 2,98E-02 | 5,36E-03 | 3,45E-02 |
| **Weighted Av.** | **774** | **3,21E-01** | **-2,73E-01** | **2,45E-02** | **2,81E-02** | **2,58E-02** | **1,57E-02** | **3,06E-02** |
| | | | | | | | | |
| **Conversion** | **Transformers** | **Max MC** | **Min MC** | **Average MC** | **St. Dev MC** | **Median MC** | **MC 25th Perc** | **MC 75th Perc.** |
| 220-220 | 38 | 1,66E-03 | 0,00E+00 | 1,21E-04 | 3,34E-04 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| 220-400 | 350 | 3,01E-03 | 0,00E+00 | 3,39E-04 | 6,90E-04 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| 400-220 | 216 | 3,21E-03 | 0,00E+00 | 7,71E-04 | 1,01E-03 | 0,00E+00 | 0,00E+00 | 1,55E-03 |
| 400-400 | 170 | 4,44E-03 | 0,00E+00 | 2,25E-04 | 8,11E-04 | 0,00E+00 | 0,00E+00 | 0,00E+00 |
| **Weighted Av.** | **774** | **4,44E-03** | **0,00E+00** | **4,24E-04** | **8,36E-04** | **0,00E+00** | **0,00E+00** | **4,33E-04** |

**Table 19: Two-winding transformers electrical characteristics summary by working voltages in per units**

| S MVA | Count | Max | Min | Average | Std Dev | Median | 25th Perc | 75th Perc |
|---|---|---|---|---|---|---|---|---|
| **R** | | | | | | | | |
| 100 | 42 | 8,00E-04 | 4,00E-05 | 4,52E-04 | 1,98E-04 | 2,78E-04 | 2,00E-04 | 4,54E-04 |
| 300 | 25 | 1,66E-03 | 0,00E+00 | 7,28E-04 | 3,90E-04 | 2,97E-04 | 2,23E-04 | 5,25E-04 |
| 400 | 160 | 7,06E-04 | 0,00E+00 | 3,04E-04 | 1,93E-04 | 3,27E-04 | 2,46E-04 | 4,60E-04 |
| 450 | 32 | 7,60E-04 | 0,00E+00 | 3,55E-04 | 1,56E-04 | 3,26E-04 | 2,76E-04 | 4,58E-04 |
| 600 | 70 | 5,13E-04 | 0,00E+00 | 2,55E-04 | 1,38E-04 | 2,89E-04 | 2,05E-04 | 5,11E-04 |
| 702,69 | 104 | 4,38E-03 | 9,00E-05 | 2,97E-04 | 4,17E-04 | 3,31E-04 | 2,83E-04 | 4,14E-04 |
| **X** | | | | | | | | |
| 100 | 42 | 3,78E-02 | 1,80E-03 | 2,10E-02 | 8,90E-03 | 2,48E-02 | 1,63E-02 | 2,94E-02 |
| 300 | 25 | 5,97E-02 | 1,00E-04 | 4,04E-02 | 1,31E-02 | 2,48E-02 | 1,72E-02 | 2,99E-02 |
| 400 | 160 | 3,92E-02 | 1,50E-02 | 2,64E-02 | 5,27E-03 | 2,56E-02 | 1,94E-02 | 2,96E-02 |
| 450 | 32 | 4,93E-02 | 2,09E-02 | 3,34E-02 | 6,62E-03 | 2,48E-02 | 1,89E-02 | 2,95E-02 |
| 600 | 70 | 3,33E-02 | -4,58E-03 | 2,41E-02 | 8,30E-03 | 2,50E-02 | 1,71E-02 | 2,98E-02 |
| 702,69 | 104 | 5,61E-02 | -1,15E-02 | 7,43E-03 | 1,67E-02 | 2,52E-02 | 1,93E-02 | 2,96E-02 |

**Table 20: Two winding transformer electrical characteristics summary by nominal power in per units**

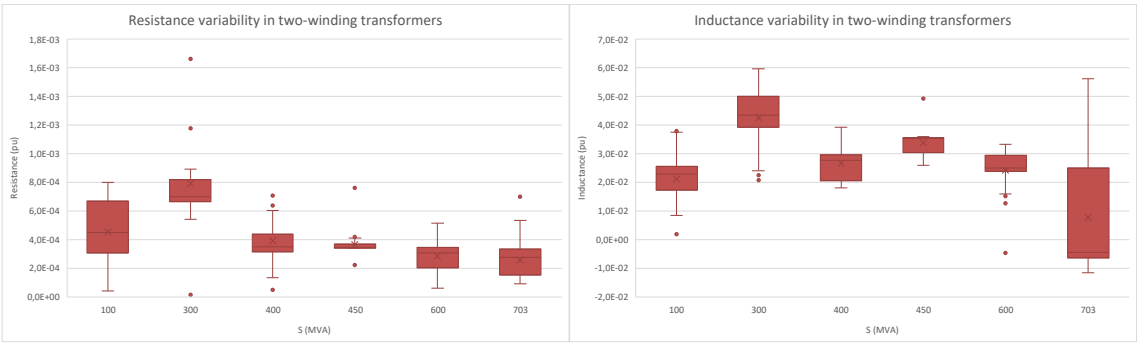



**Figure 67: Resistance and Reactance variability in two-winding transformers**

It is also interesting to illustrate the sum of the maximum power that enters into a node and the nominal power of the transformer connected to said nodes. Figure 68 shows the variability of the power that enters into a node with respect to the same nominal powers of transformers analysed previously.

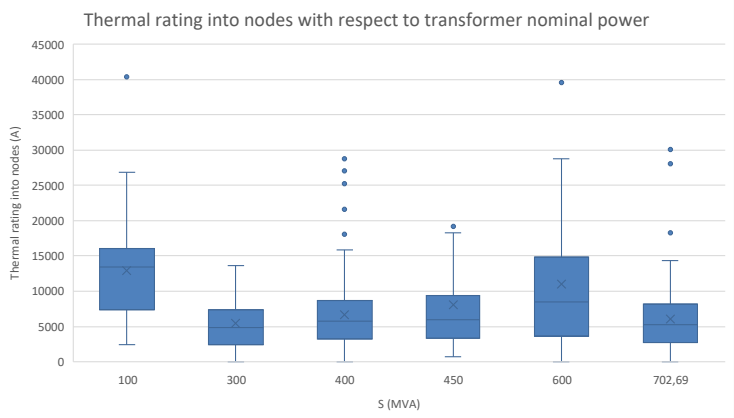



**Figure 68: Thermal rating into nodes with respect to two-winding transformer nominal power**

### 3.1.2. Three-Winding Transformer data

The three winding transformers are equivalent to three-single-phase-two-winding transformers but using less ferromagnetic material than having three separate single-phase transformers. Table 21 shows a summary of the electrical characteristics of the 286 three winding transformers provided by ENTSO-E. The voltage levels ignore the auxiliary voltage level, focusing on the main power-line levels. Table 22 shows the same data but by nominal power. The number of transformers in this table is less than the aforementioned 286, due to the main nominal powers being chosen. There are many different nominal power levels throughout Europe, but the chosen ones are the most frequent ones, for which a more trustworthy conclusion can be drawn. Figure 69, Figure 70 and Figure 71 illustrate the resistance and reactance variability in each of the three windings of the three-winding transformers included in Table 22.

| | Max | Min | Average | Std Dev | Median | 25th Perc | 75th Perc |
|---|---|---|---|---|---|---|---|
| **Winding 1 R** | 1,20E-03 | 7,80E-05 | 3,21E-04 | 1,71E-04 | 2,30E-04 | 2,08E-04 | 4,00E-04 |
| **Winding 2 R** | 8,89E-03 | 0,00E+00 | 1,60E-03 | 1,15E-03 | 1,18E-03 | 1,00E-03 | 1,68E-03 |
| **Winding 3 R** | 8,89E-03 | 0,00E+00 | 1,63E-03 | 1,16E-03 | 1,19E-03 | 1,00E-03 | 1,82E-03 |
| **Winding 1 X** | 8,21E-02 | 1,42E-02 | 2,38E-02 | 8,24E-03 | 1,94E-02 | 1,85E-02 | 2,98E-02 |
| **Winding 2 X** | 3,37E-01 | 2,97E-02 | 6,03E-02 | 3,14E-02 | 5,60E-02 | 3,65E-02 | 7,59E-02 |
| **Winding 3 X** | 3,29E-01 | 3,65E-02 | 8,93E-02 | 3,74E-02 | 7,69E-02 | 5,85E-02 | 1,11E-01 |
| **MC** | 3,55E-03 | 0,00E+00 | 7,30E-04 | 1,15E-03 | 0,00E+00 | 0,00E+00 | 1,42E-03 |

**Table 21: Three-winding transformers electrical characteristics summary by voltage level in per units**

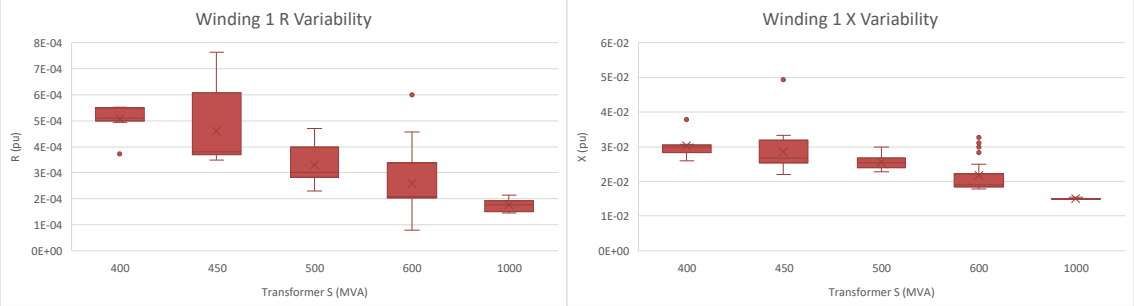



**Figure 69: Winding 1 resistance and reactance variability**

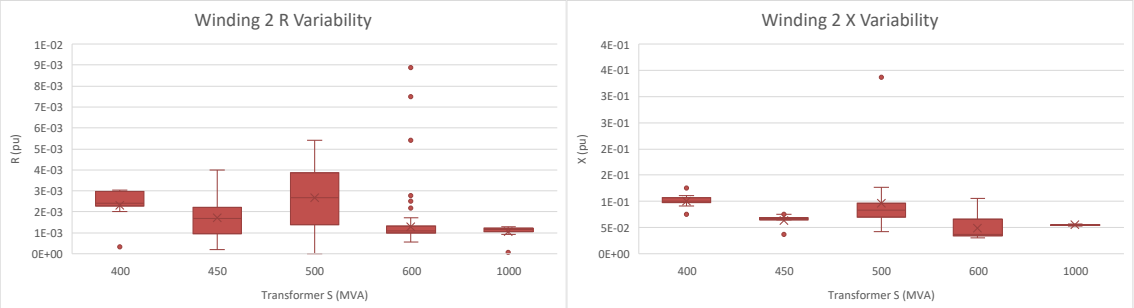



**Figure 70: Winding 2 resistance and reactance variability**

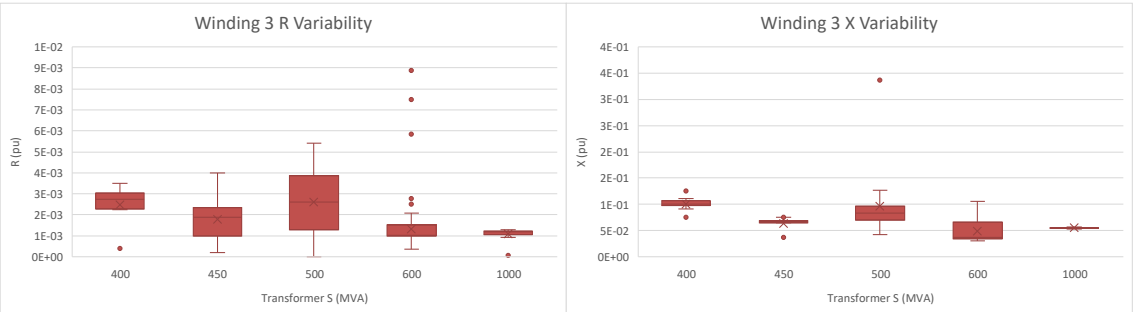



**Figure 71: Winding 3 resistance and reactance variability**

| S MVA | Count | Max | Min | Average | Std Dev | Median | 25th Perc | 75th Perc |
|---|---|---|---|---|---|---|---|---|
| **R1** | | | | | | | | |
| 400 | 17 | 5,53E-04 | 3,72E-04 | 5,07E-04 | 5,27E-05 | 2,30E-04 | 2,08E-04 | 4,00E-04 |
| 450 | 20 | 7,62E-04 | 3,48E-04 | 4,60E-04 | 1,38E-04 | 2,30E-04 | 2,08E-04 | 4,00E-04 |
| 500 | 21 | 4,70E-04 | 2,30E-04 | 3,31E-04 | 6,47E-05 | 2,30E-04 | 2,08E-04 | 4,00E-04 |
| 600 | 151 | 6,00E-04 | 7,80E-05 | 2,59E-04 | 9,77E-05 | 2,30E-04 | 2,08E-04 | 4,00E-04 |
| 1000 | 13 | 2,14E-04 | 1,46E-04 | 1,76E-04 | 2,44E-05 | 2,30E-04 | 2,08E-04 | 4,00E-04 |
| **R2** | | | | | | | | |
| 400 | 17 | 3,03E-03 | 3,13E-04 | 2,31E-03 | 8,18E-04 | 1,18E-03 | 1,00E-03 | 1,68E-03 |
| 450 | 20 | 4,00E-03 | 2,00E-04 | 1,71E-03 | 9,31E-04 | 1,18E-03 | 1,00E-03 | 1,68E-03 |
| 500 | 21 | 5,40E-03 | 0,00E+00 | 2,66E-03 | 1,63E-03 | 1,18E-03 | 1,00E-03 | 1,68E-03 |
| 600 | 151 | 8,89E-03 | 3,69E-04 | 1,30E-03 | 9,37E-04 | 1,18E-03 | 1,00E-03 | 1,68E-03 |
| 1000 | 13 | 1,28E-03 | 7,40E-05 | 1,06E-03 | 3,15E-04 | 1,18E-03 | 1,00E-03 | 1,68E-03 |
| **R3** | | | | | | | | |
| 400 | 17 | 3,50E-03 | 4,06E-04 | 2,49E-03 | 8,83E-04 | 1,19E-03 | 1,00E-03 | 1,82E-03 |
| 450 | 20 | 4,00E-03 | 2,00E-04 | 1,79E-03 | 9,65E-04 | 1,19E-03 | 1,00E-03 | 1,82E-03 |
| 500 | 21 | 5,40E-03 | 0,00E+00 | 2,60E-03 | 1,66E-03 | 1,19E-03 | 1,00E-03 | 1,82E-03 |
| 600 | 151 | 8,89E-03 | 3,78E-04 | 1,34E-03 | 9,57E-04 | 1,19E-03 | 1,00E-03 | 1,82E-03 |
| 1000 | 13 | 1,28E-03 | 7,40E-05 | 1,07E-03 | 3,21E-04 | 1,19E-03 | 1,00E-03 | 1,82E-03 |
| **X1** | | | | | | | | |
| 400 | 17 | 3,77E-02 | 2,60E-02 | 3,02E-02 | 3,16E-03 | 1,94E-02 | 1,85E-02 | 2,98E-02 |
| 450 | 20 | 4,93E-02 | 2,20E-02 | 2,85E-02 | 6,06E-03 | 1,94E-02 | 1,85E-02 | 2,98E-02 |
| 500 | 21 | 3,00E-02 | 2,27E-02 | 2,55E-02 | 1,92E-03 | 1,94E-02 | 1,85E-02 | 2,98E-02 |
| 600 | 151 | 3,27E-02 | 1,78E-02 | 2,18E-02 | 5,25E-03 | 1,94E-02 | 1,85E-02 | 2,98E-02 |
| 1000 | 13 | 1,55E-02 | 1,48E-02 | 1,51E-02 | 1,88E-04 | 1,94E-02 | 1,85E-02 | 2,98E-02 |
| **X2** | | | | | | | | |
| 400 | 17 | 1,25E-01 | 7,49E-02 | 1,01E-01 | 1,05E-02 | 5,60E-02 | 3,65E-02 | 7,59E-02 |
| 450 | 20 | 8,32E-02 | 3,65E-02 | 6,39E-02 | 1,27E-02 | 5,60E-02 | 3,65E-02 | 7,59E-02 |
| 500 | 21 | 3,37E-01 | 4,27E-02 | 9,58E-02 | 5,93E-02 | 5,60E-02 | 3,65E-02 | 7,59E-02 |
| 600 | 151 | 1,05E-01 | 2,97E-02 | 4,82E-02 | 1,80E-02 | 5,60E-02 | 3,65E-02 | 7,59E-02 |
| 1000 | 13 | 5,66E-02 | 5,25E-02 | 5,50E-02 | 1,11E-03 | 5,60E-02 | 3,65E-02 | 7,59E-02 |
| **X3** | | | | | | | | |
| 400 | 17 | 1,72E-01 | 1,20E-01 | 1,44E-01 | 1,17E-02 | 7,69E-02 | 5,85E-02 | 1,11E-01 |
| 450 | 20 | 1,33E-01 | 5,85E-02 | 9,69E-02 | 1,98E-02 | 7,69E-02 | 5,85E-02 | 1,11E-01 |
| 500 | 21 | 2,12E-01 | 7,44E-02 | 1,23E-01 | 3,04E-02 | 7,69E-02 | 5,85E-02 | 1,11E-01 |
| 600 | 151 | 1,16E-01 | 3,65E-02 | 7,39E-02 | 2,31E-02 | 7,69E-02 | 5,85E-02 | 1,11E-01 |
| 1000 | 13 | 8,35E-02 | 6,80E-02 | 7,65E-02 | 4,02E-03 | 7,69E-02 | 5,85E-02 | 1,11E-01 |
| **MC** | | | | | | | | |
| 400 | 17 | 1,32E-03 | 0,00E+00 | 2,99E-04 | 5,57E-04 | 0,00E+00 | 0,00E+00 | 1,42E-03 |
| 450 | 20 | 1,44E-03 | 0,00E+00 | 5,98E-04 | 6,80E-04 | 0,00E+00 | 0,00E+00 | 1,42E-03 |
| 500 | 21 | 1,20E-03 | 0,00E+00 | 2,68E-04 | 4,92E-04 | 0,00E+00 | 0,00E+00 | 1,42E-03 |
| 600 | 151 | 3,55E-03 | 0,00E+00 | 5,96E-04 | 1,16E-03 | 0,00E+00 | 0,00E+00 | 1,42E-03 |
| 1000 | 13 | 2,88E-03 | 1,71E-03 | 2,48E-03 | 3,51E-04 | 0,00E+00 | 0,00E+00 | 1,42E-03 |

**Table 22: Three winding transformers electrical characteristic summary by nominal power in per units**

Finally, and similarly to two-winding transformers, the sum of the thermal ratings into a node is compared to the nominal power of the transformer connected to that node. Figure 72 illustrated this relationship.

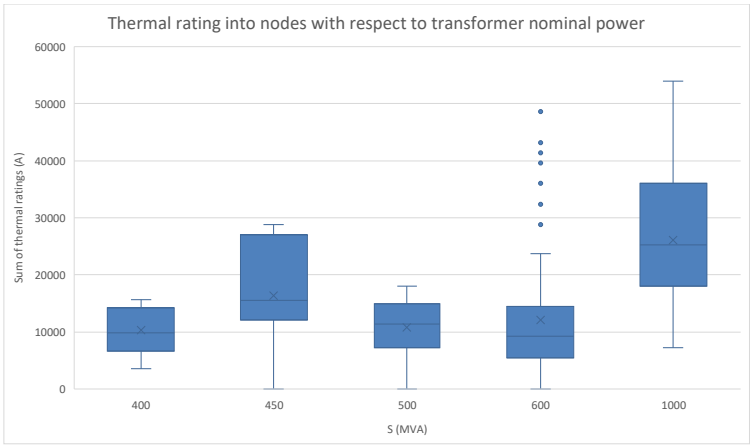



**Figure 72: Thermal rating into nodes against three-winding transformer nominal power**

## 3.2. Shunt Characteristic model

Shunts are used to regulate voltage levels at nodes in the network. They are intended to counteract the generation or consumption of reactive power caused by power flowing through the transmission lines by generating reactive power and as a consequence elevating the voltage level. This is the case when working under high loads, but lines can have the opposite effect by consuming reactive power in scenarios of small power transfers. In this case, voltage levels rise in sub-stations and can harm both infrastructure and consumer appliances. To mitigate this, instead of using capacitive shunts, inductive shunts are used, which generate reactive power and counteract the effect. Some shunts have a variable nature, allowing them to switch how much reactive power they consume depending on the state of the network, and some are fixed. Both cases are contained within the ENTSO-E data and will be explored. Figure 73 illustrates simply what the parameters of the shunts refer to.

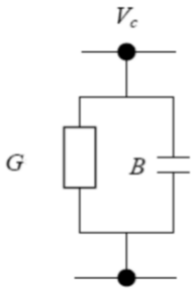



**Figure 73: Shunt equivalent circuit**

### 3.2.1. Fixed Shunts

In fixed shunts, ENTSO-E provides information about both B and G. All G-shunt values are positive as they are all resistive loads, but the B-Shunt values take positive and

negative values. This is due to the existence of inductive and capacitive shunts. Figure 74 and Figure 75 illustrate this information.

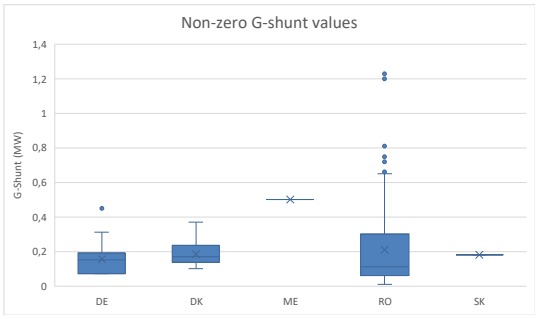



**Figure 74: Variability in non-zero G-shunt values**

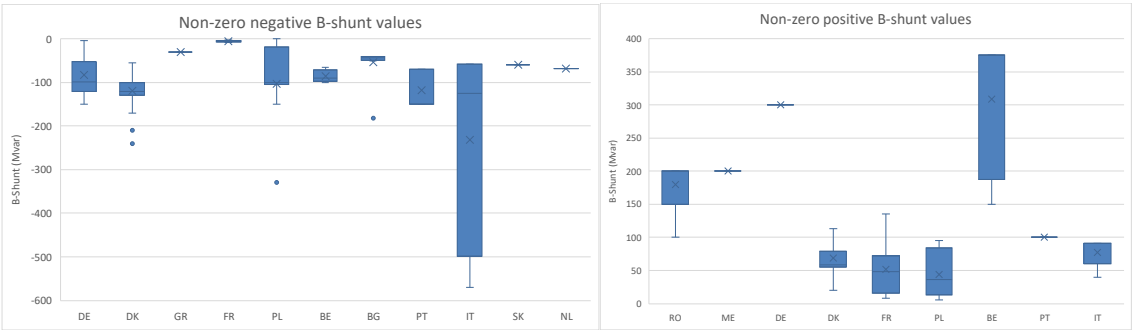



**Figure 75: Variability in non-zero B-shunt values separated into inductive and capacitive, or positive and negative values respectively**

Another measure that is interesting to note about shunts if the shunt value linked to the thermal rating of the lines that enter into it. This links graph theory with the information linked. It should be the case that at higher voltages and higher thermal ratings feeding into a node, the shunt value should be larger, moving from an inductive load to a capacitive load. In a way this is linked to the degree of the node, but simply the degree is not sufficient as not all connections to a node are equal. Figure 76 illustrates this relationship.

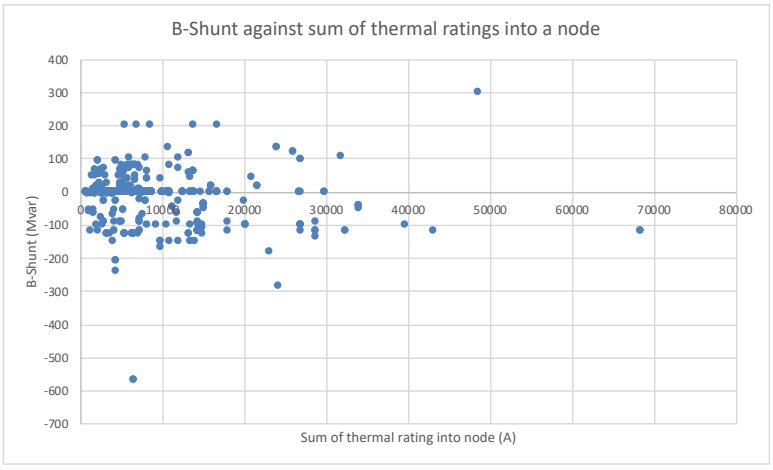



**Figure 76: B-shunt against sum of thermal ratings into a node**

### 3.2.2. Switched Shunts

Switched shunts provided be ENTSO-E are not given with a G-Shunt value, they are only considered to have reactive power consumption or generation, and no active power consumption. Switched shunt information is given for Denmark, Spain, France, Greece and the Netherlands. The shunts are classified as those with one, two or three steps. Some of the shunts have a fixed minimum value, some are able to be disconnected entirely. Figure 77, Figure 78 and Figure 79 illustrate the data. The number of shunts that fall into each category are summarised in Table 23.

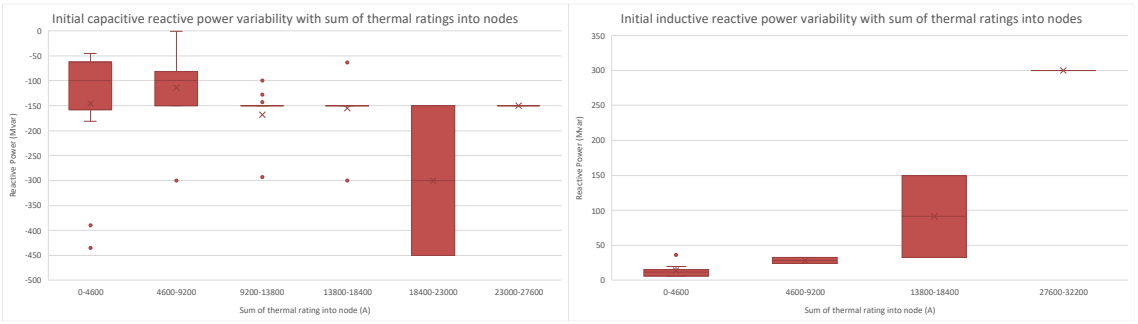



**Figure 77: Initial reactive power variability with respect to sum of thermal ratings into nodes**

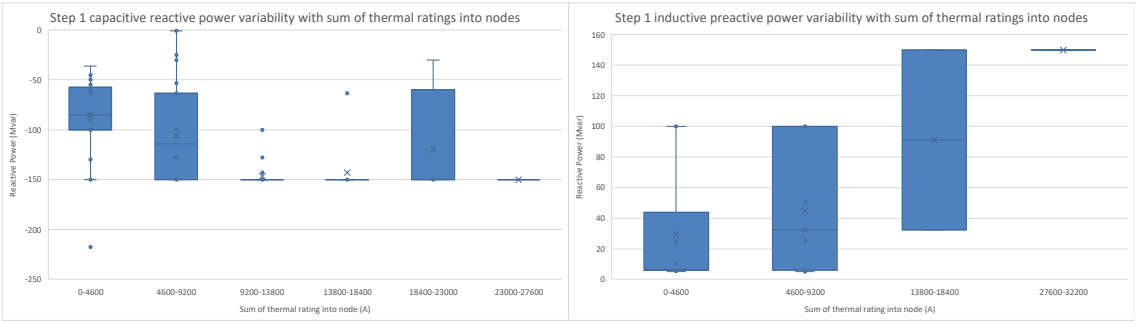



**Figure 78: Step 1 reactive power variability with respect to sum of thermal ratings into nodes**

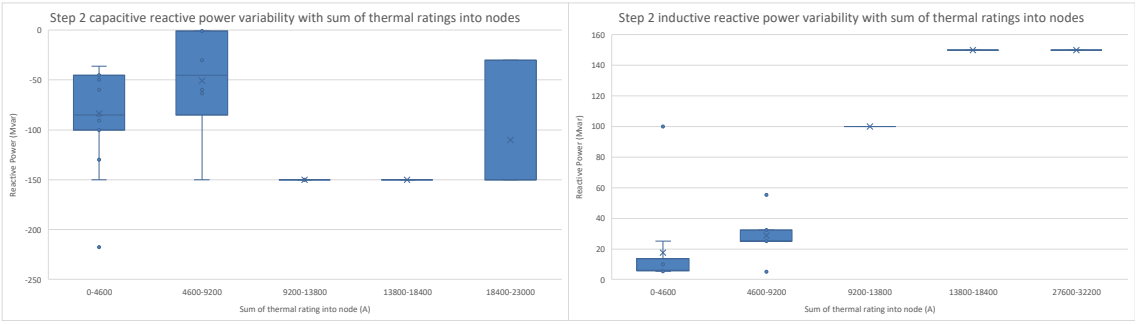



**Figure 79: Step 2 reactive power variability with respect to sum of thermal ratings into nodes**

| Thermal rating sum (A) | Initial Reative Power (Mvar) | Step 1 (Mvar) | Step 2 (Mvar) | Step 3 (Mvar) |
|---|---|---|---|---|
| 0-4600 | 23 | 56 | 15 | 1 |
| 4600-9200 | 19 | 51 | 13 | 1 |
| 9200-13800 | 20 | 25 | 8 | 0 |
| 13800-18400 | 14 | 14 | 3 | 0 |
| 18400-23000 | 3 | 4 | 3 | 1 |
| 23000-27600 | 1 | 1 | 0 | 0 |
| 27600-32200 | 1 | 1 | 1 | 0 |
| **Grand Total** | **81** | **152** | **43** | **3** |

**Table 23: Shunt numbers at different node thermal rating sums**

In total, there are only three shunts that have a third step, all of them in Spain, with values of -150 MVAr two of them and 6 MVAr.

# 4. Discussion

The proposed methodology to validate the data will consist on looking at the different parameters analysed and proposing a range of values to be used in any validation application. Resistance, reactance, capacitive susceptance and thermal rating are the parameters under study. They will all be based on the information available and any inferences made will be explained. For the countries that provide information about the length of lines, their values will be analysed separately.

## 4.1. Global Aspects

The main global aspects of this validation start with separating all the values between transmission lines at 220 kV and 400 kV. Values appear to differ considerably more between voltage levels than within them, leading to this separation.

Furthermore, as the data is provided by different TSO's with different criteria with respect to data acquisition and design criteria (using a certain tower, cable type or number of conductors per circuit), consistency in the data within countries is higher than between them, leading to this separation.

All parameters, be it thermal rating, resistance, reactance or capacitive susceptance, are verified to be within certain thresholds first before making assumptions, all outliers will be questioned as their value might not be in line with the overall picture.

## 4.2. Thermal Rating

Firstly, to try to characterise lines, thermal rating will be analysed. Once the value has been verified to be within the established ranges, it is interesting to look for any

relationship between thermal rating and any other parameter. There does not seem to be a clear relationship between thermal rating and line length. In the countries that provide line length data, there seem to be several typical thermal ratings which can be observed for lines of all lengths. Figure 37, Figure 44, Figure 55 and Figure 64 illustrate this assumption for the different countries available.

With respect to the relationship between thermal rating and resistance there does not seem to be a clear causal relationship between resistance and thermal rating. Lines of a given thermal rating in general have a broad diversity of resistances, as con be observed in Figure 7 and Figure 8. Similarly, in line reactance and capacitive susceptance, these values for a line seem to be relatively random with respect to thermal rating as can be observed in Figure 15, Figure 16, Figure 23 and Figure 24. Although there seems to be typical values for thermal ratings, these have a variety of reactance values regardless of their thermal rating value.

There does seem however to be at least a range criterion that can be applied to the relationship between thermal rating and X/R. As can be observed in Figure 19 and Figure 20 for the overall data from ENTSO-E, a ratio between thermal rating and X/R between 100 and 33 MVA for lines at 220 kV and between 250 and 50 for lines at 400 kV seems a safe yet broad validation criteria. This is confirmed by the data provided by RTE, as can be observed in Figure 38, with ratios of 250 to 125 for lines at 220 kV and 300 to 200 for lines at 400 kV. This is also observable to a lesser degree for lines in Spain and Portugal, Belgium and Denmark in Figure 45, Figure 56 and Figure 65.

Finally, in the relationships found in Figure 7 and Figure 8, it can be observed that, generally and for the whole of the data published by ENTSO-E, the main thermal rating values hover around or below 500 MVA in lines at 220 kV. Nevertheless, there are some lines above 1000 MVA. At 400 kV, the line thermal ratings are much higher, being the majority of the lines within the 1000 to 2000 MVA range.

### 4.3. Resistance

Resistance absolute values are in general lower for lines at 220 kV than for lines at 400 kV, as can be observed in Table 1 and Table 2. A way to validate a line resistance value is to verify it is within the maximum and minimum limits of lines in the European system. In particular, they can be within the maximum and minimum values observable on the aforementioned tables per country. Lines with resistances above 13 Ω should be closely analysed in case they are outliers. In the ENTSO-E data there are many lines with no

resistance. This should not be considered appropriate when assigning values, and if such a value is assigned it should be closely inspected. Falling between the 2nd and 98th percentiles in Table 1 and Table 2 should be a good indication that, per country, the resistances assigned are appropriate.

Possibly the best way to validate a resistance value is to use the length of the line generated by the synthetic network. From the data from France, Spain, Portugal, Denmark and Sweden, observable in Figure 29, Figure 30, Figure 40, Figure 48, Figure 49, Figure 57 and Figure 58, the resistance per unit length varies from 3 to 9 $\frac{\Omega}{\text{km}} * 10^{-2}$ for lines at 220 kV and from 2 to 5 $\frac{\Omega}{\text{km}} * 10^{-2}$ for lines at 400 kV. This variation on the data could be due to multiple conductors per circuit causing resistance to diminish greatly, as can be seen in Table 24 and Table 25. To make this comparison with length of line, it is important to make a slight adjustment in the length of the line to account for lines being longer in reality to the spherical straight-line distance between the nodes it joins. From Figure 39 it can be seen that the shorter the line, independently of the number of circuits it has, the larger the percentage difference between real and straight-line distance. The values to use as multiples should be to add a 25% to lines below 40 km and 15 % to lines above 40 km.

Although these values are for four countries only, any deviation from these values globally should be carefully scrutinised.

### 4.4. Reactance

Reactance follows a similar trend to resistance in that of resistance, in this case with general values being slightly higher for 400 kV than 220 kV. As a first validation step, no line reactance should be outside the maximum and minimum values seen in Table 6 and Table 7, although as the maximum values are very different from the values of the 75th percentile, any value above said percentile should be scrutinised, and any value outside the absolute maximum or minimum for each country should be analysed more heavily.

Yet again, a very elegant check made possible by the information provided by France, Spain, Portugal, Denmark and Sweden allows the relationship between reactance and length of line to be validated. Figure 31, Figure 32,

Figure 41, Figure 50, Figure 51, Figure 59 and Figure 60 show how reactance values are around 2 to 4 $\frac{\Omega}{\text{km}} * 10^{-1}$ for lines at 220 kV and between 2 and 3.5 $\frac{\Omega}{\text{km}} * 10^{-1}$ for lines at

400 kV. Using multiple conductors per circuit does not affect the reactance per unit length as it does resistance, as can be observed in Table 24 and Table 25. Using a multiple for line length as with resistance should be done to emulate real line length compared to spherical straight-line length.

The resistance and reactance of lines are directly linked to the length of said line, which is information we don't have available about all lines but would have in the case of a synthetic network. However, a relative comparison between both of them can be drawn from Table 11. These relationships between reactance and resistance can be observed in all figures from Figure 82 to Figure 212. These show the overall picture for a given country and the individual relationships found within it. These relationships are accompanied in Table 11 by a relative multiple from the smallest to the highest per country. This allows one to observe if the reason for the existence of multiple lines is due to the lines being composed of more than one conductor per circuit, i.e. simplex, duplex or triplex lines. The theoretical multiples can be observed in Table 26.

### 4.5. Capacitive Susceptance

Capacitive susceptance values can be generally constrained by the maximum and minimum values appreciable per country in Table 12 and Table 13, as with resistance and reactance. The 2$^{nd}$ and 98$^{th}$ percentiles are more constrained than the maximum values per country and should be used to further validate the values assigned to lines.

The most important relationship observable in all the lines in France, Spain, Portugal, Denmark and Sweden if the relationship between capacitive susceptance and distance. Figure 33, Figure 34, Figure 43, Figure 53, Figure 54, Figure 62 and Figure 63 show how this relationship is very near 2 $\frac{\mu S}{km}$ for all lines and voltage levels, varying 1 $\frac{\mu S}{km}$ between countries and voltage levels. It is important to use the correction factor for real length with respect to spherical straight-line length, as with all previous electrical parameters.

### 4.6. Transformers

In terms of transformers, the available data is slightly different to the previously described line characteristics. Two winding and three winding transformers are typified by ENTSO-E, and data about the resistance, reactance and magnetizing capacitance is described. The difference between both types of transformers appears to be the modal nominal powers, being from 100 to 700 MVA for two winding transformers and between 400 and 1000 MVA for three winding transformers. These are the boundaries to be checked when a

transformer is sized, although transformers are sized on a per case basis, meaning there are many different values available. The ones described in this paper are, as specified beforehand, only the modal nominal powers.

The resistance and reactance of the different windings in two winding transformers at the modal nominal powers, in per units, can be seen in Table 20, and the maximum values should be ideally respected. Any value above the maximum values should be heavily scrutinised. Furthermore, with the $75^{th}$ percentile information available, any value larger than these percentiles for a given transformer should be at least questioned.

In terms of three winding transformers, a clearer trend of decreasing resistance and reactance with increasing nominal power can be observed in Figure 69, Figure 70 and Figure 71. Table 21 and Table 22 show the tabulated figures shows in the aforementioned figures. Respecting maximums and minimums, as well as $25^{th}$ and $75^{th}$ percentiles should be a reasonable validation requirement.

An interesting measure, closely related to the degree of a node in graph theory, is to compare the nominal power of a transformer to the sum of the thermal rating of the lines connected to it. From the results observable in Figure 68 and Figure 72, in general the thermal rating into a node connected to a transformer is of the order of 3,000 to 15,000 amps for two winding transformers and 5,000 to 20,000 amps for three winding transformers.

### 4.7. Shunts

Shunts are distinguished between fixed and switched by ENTSO-E. Within these, different values can be used to validate the data and assure a correct value is assigned to a shunt should a node require it in a synthetic network. Values are quoted in MVAr, instead of per units.

Fixed shunts take a broad variety of values. G-shunt values should lie within 0.1 and 0.3 MW whereas B-shunt values are clearly separated into negative and positive, or capacitive and inductive, with values illustrated in Figure 75. Negative, or capacitive, values are clustered around 100 MVAr, also observable in Figure 76, whereas positive, or inductive, values are usually below 100 MVAr. There doesn't seem to a be a significant relationship between thermal ratings into nodes and the size of a fixed shunt.

Switched shunts are described with an initial reactive power setting, as well as a stepped increase, up to three steps in some cases. These steps need not have relation between them

but are usually of similar size. A simple check of orders of magnitude should be sufficient, although the values can be seen in Figure 77, Figure 78 and Figure 79. Capacitive reactive power, similarly to that of sixed shunts, is centred around 150 MVAr, with slightly increasing values as thermal rating into a node increases. Similarly, for initial inductive reactive power values increase steadily from below 50 MVAr to 300 MVAr as thermal rating into nodes increases. This can be observed in Figure 77. Table 23 summarises the number of shunts per thermal rating sum into node interval, with detail on the number of shunts that have more than one step.

# 5. Proposed validation methodology

The validation methodology is based entirely on the workflow described in the discussion. From the flow chart in Figure 80 and Figure 81, all the values can be classified into three categories. Firstly, all the values that do not comply with any filter, should be discarded and included in a "red" category. Secondly, all the values that fulfil the maximum-minimum criteria but not the 2-98% criteria's should be included in a "yellow" bucket and should be scrutinised before being included in the "green" bucket, where the values that flow through the whole flow chart should be included.

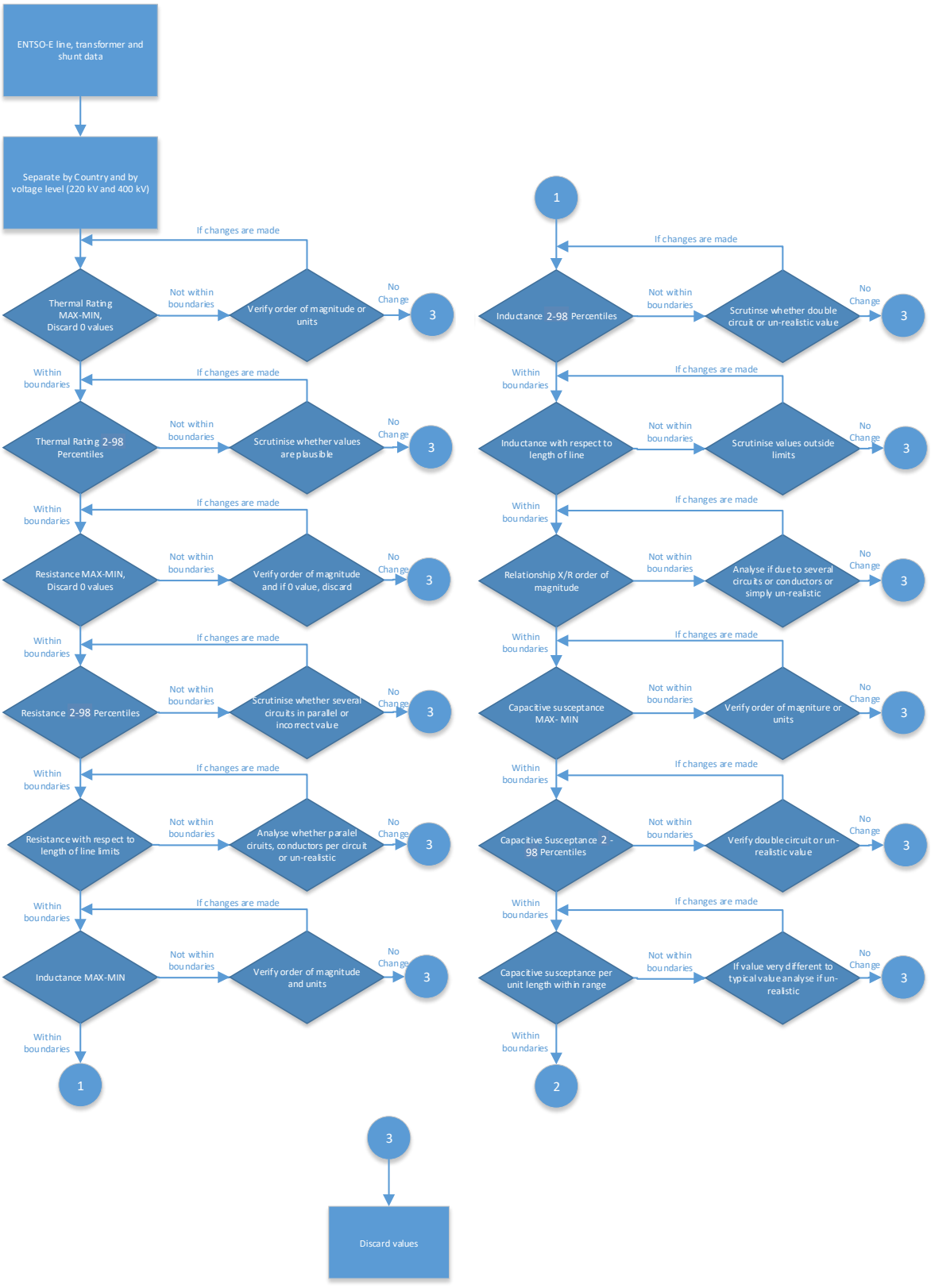



**Figure 80: Part 1 and 2 of data validation decision tree**

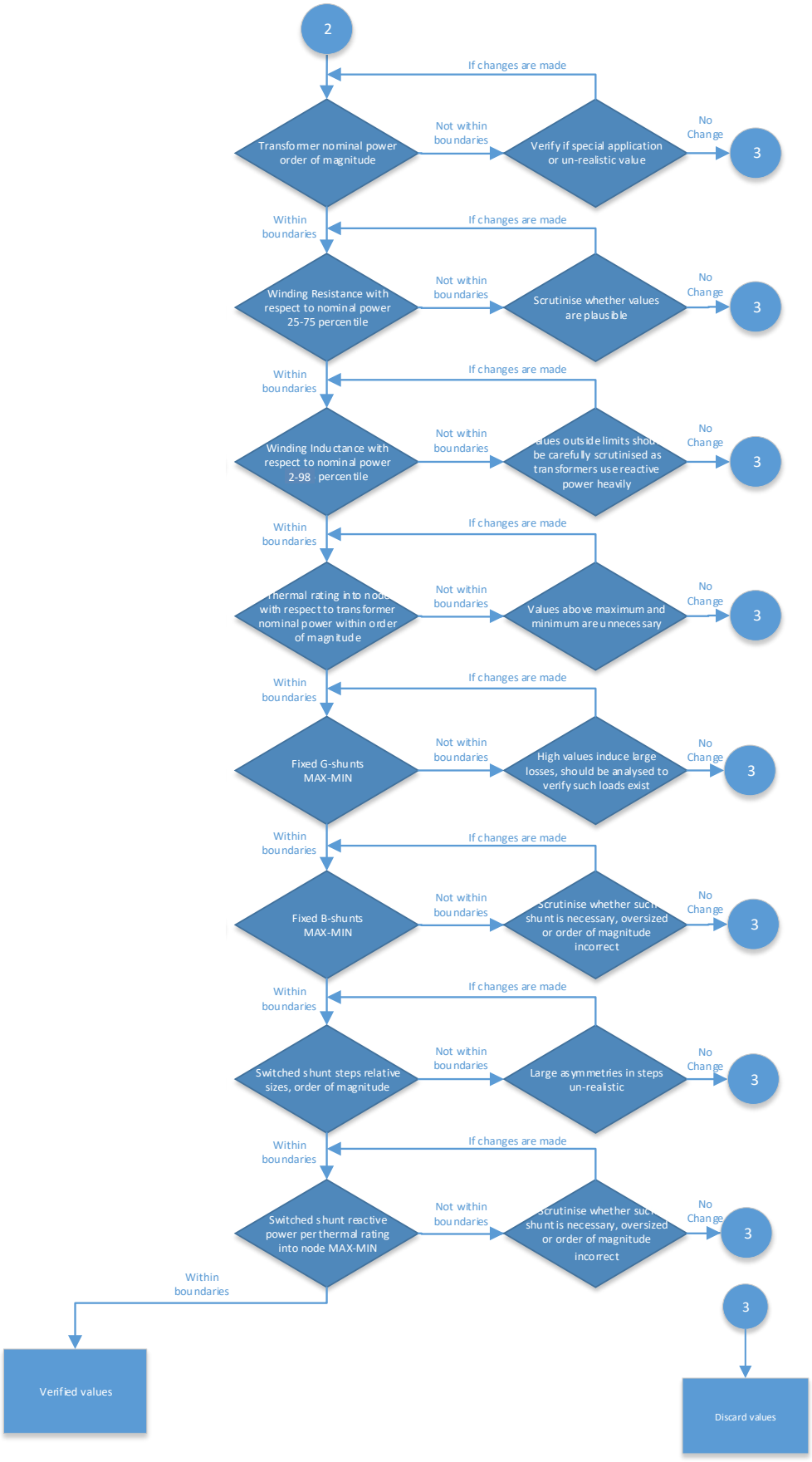



**Figure 81: Part 3 of data validation decision tree**

# 6. Conclusions

At this stage in the development of publicly available data sets of information about electricity transmission grids, it is very interesting to make use of these in a coherent and thoughtful way. This project has shown how it is possible to use the data available in a coherent manner and find it's similarity with the theory behind it. A validation methodology has been developed that can be applied to any data set it is presented with.

The data published by ENTSO-E and other TSO's, such as RTE, are solely a reference point for this study, and therefore the results obtained should be considered as such, only criteria designed to be implemented with whichever training set is used. If a different set of lines is used, the validity of the conclusions made might be different to those made in this project.

The proposed methodology to validate the data consists on looking at the different parameters analysed and proposing a range of to be used in any validation application. Resistance, reactance, capacitive susceptance and thermal rating have been studied. All the methodology is based on the information available. For the countries that provide information about the length of lines, their values have been analysed separately.

The validation methodology is based entirely on the workflow described in the discussion. A decision tree methodology has been used in order to verify all values individually, and the data table where the statistics are summarised per country and voltage levels are Table 1, Table 2, Table 6, Table 7, Table 12 and Table 13. Minimum and maximum values constitute the first filter, followed by a 2% to 98% percentiles, justifying values that lie outside these values. Lastly, the verification of the ratios viewable in Table 11, Figure 46 and Figure 47 is an interesting measure of validity. A similar verification can be done to data describing transformers and shunts, whose ranges can be observed in Table 22 and Table 23. All the values that do not comply with any filter, are discarded and included in a "red" category. Secondly, all the values that fulfil the maximum-minimum criteria but not the 2-98% criteria's are included in a "yellow" bucket and should be scrutinised before being included in the "green" bucket, where the values that flow through the whole flow chart should be included.

The decision tree with detailed steps can be seen in Figure 80 and Figure 81.

# 7. Acknowledgments

The author would like to thank Rafael Espejo for his help and dedication during the investigation behind this project, as well as Andrés Ramos and Sara Lumbreras for their assistance during said fulfilment.

Likewise, the author would like to thank his family for being a constant support during the six years that have led to this project, it would not have been possible without them.

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# 9. Appendix

## 9.1. Cable type and configuration effects on electrical parameters

| Hawk | | Single Circuit | | Double Circuit | | Condor | | Single Circuit | | Double Circuit | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| /km | | 1 | 2 | 3 | 4 | /km | | 1 | 2 | 3 | 4 |
| Simplex | R ohm | 1,12E-01 | 1,12E-01 | 5,62E-02 | 5,62E-02 | Simplex | R ohm | 6,75E-02 | 6,75E-02 | 3,37E-02 | 3,37E-02 |
| | X ohm | 4,67E-01 | 4,66E-01 | 2,29E-01 | 2,38E-01 | | X ohm | 4,51E-01 | 4,50E-01 | 2,21E-01 | 2,30E-01 |
| | B S | 2,44E-06 | 2,44E-06 | 4,97E-06 | 4,78E-06 | | B S | 2,53E-06 | 2,53E-06 | 5,15E-06 | 4,95E-06 |
| Duplex | R ohm | 5,62E-02 | 5,62E-02 | 2,81E-02 | 2,81E-02 | Duplex | R ohm | 3,37E-02 | 3,37E-02 | 1,69E-02 | 1,69E-02 |
| | X ohm | 3,32E-01 | 3,31E-01 | 1,62E-01 | 1,70E-01 | | X ohm | 3,24E-01 | 3,23E-01 | 1,58E-01 | 1,66E-01 |
| | B S | 3,39E-06 | 3,40E-06 | 6,97E-06 | 6,60E-06 | | B S | 3,48E-06 | 3,48E-06 | 7,15E-06 | 6,76E-06 |
| Triplex | R ohm | 3,75E-02 | 3,75E-02 | 1,87E-02 | 1,87E-02 | Triplex | R ohm | 2,25E-02 | 2,25E-02 | 1,12E-02 | 1,12E-02 |
| | X ohm | 4,12E-01 | 4,12E-01 | 2,02E-01 | 2,11E-01 | | X ohm | 4,07E-01 | 4,06E-01 | 1,99E-01 | 2,08E-01 |
| | B S | 2,70E-06 | 2,70E-06 | 5,52E-06 | 5,28E-06 | | B S | 2,74E-06 | 2,74E-06 | 5,59E-06 | 5,35E-06 |

| Hawk | | Single Circuit | | Double Circuit | | Condor | | Single Circuit | | Double Circuit | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | | | 1 | 2 | 3 | 4 |
| Simplex | R ohm | 100% | 100% | 50% | 50% | Simplex | R ohm | 100% | 100% | 50% | 50% |
| | X ohm | 100% | 100% | 49% | 51% | | X ohm | 100% | 100% | 49% | 51% |
| | B S | 100% | 100% | 204% | 196% | | B S | 100% | 100% | 204% | 196% |
| Duplex | R ohm | 50% | 50% | 25% | 25% | Duplex | R ohm | 50% | 50% | 25% | 25% |
| | X ohm | 71% | 71% | 35% | 37% | | X ohm | 72% | 72% | 35% | 37% |
| | B S | 139% | 140% | 286% | 271% | | B S | 138% | 138% | 283% | 268% |
| Triplex | R ohm | 33% | 33% | 17% | 17% | Triplex | R ohm | 33% | 33% | 17% | 17% |
| | X ohm | 88% | 88% | 43% | 45% | | X ohm | 90% | 90% | 44% | 46% |
| | B S | 111% | 111% | 227% | 217% | | B S | 108% | 108% | 221% | 212% |

**Table 24: Comparison of different electrical parameters per kilometer for Hawk and Condor cable types**

| Gull | | Single Circuit | | Double Circuit | | Cardinal | | Single Circuit | | Double Circuit | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| /km | | 1 | 2 | 3 | 4 | /km | | 1 | 2 | 3 | 4 |
| Simplex | R ohm | 8,05E-02 | 8,05E-02 | 4,03E-02 | 4,03E-02 | Simplex | R ohm | 5,62E-02 | 5,62E-02 | 2,81E-02 | 2,81E-02 |
| | X ohm | 4,56E-01 | 4,56E-01 | 2,24E-01 | 2,33E-01 | | X ohm | 4,45E-01 | 4,44E-01 | 2,18E-01 | 2,27E-01 |
| | B S | 2,49E-06 | 2,50E-06 | 5,09E-06 | 4,89E-06 | | B S | 2,56E-06 | 2,56E-06 | 5,22E-06 | 5,01E-06 |
| Duplex | R ohm | 4,03E-02 | 4,03E-02 | 2,01E-02 | 2,01E-02 | Duplex | R ohm | 2,81E-02 | 2,81E-02 | 1,41E-02 | 1,41E-02 |
| | X ohm | 3,27E-01 | 3,26E-01 | 1,59E-01 | 1,68E-01 | | X ohm | 3,21E-01 | 3,20E-01 | 1,56E-01 | 1,65E-01 |
| | B S | 3,45E-06 | 3,45E-06 | 7,09E-06 | 6,70E-06 | | B S | 3,51E-06 | 3,52E-06 | 7,22E-06 | 6,82E-06 |
| Triplex | R ohm | 2,68E-02 | 2,68E-02 | 1,34E-02 | 1,34E-02 | Triplex | R ohm | 1,87E-02 | 1,87E-02 | 9,37E-03 | 9,37E-03 |
| | X ohm | 4,09E-01 | 4,08E-01 | 2,00E-01 | 2,09E-01 | | X ohm | 4,05E-01 | 4,04E-01 | 1,98E-01 | 2,07E-01 |
| | B S | 2,72E-06 | 2,73E-06 | 5,57E-06 | 5,33E-06 | | B S | 2,75E-06 | 2,75E-06 | 5,62E-06 | 5,38E-06 |

| Gull | | Single Circuit | | Double Circuit | | Cardinal | | Single Circuit | | Double Circuit | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | | | 1 | 2 | 3 | 4 |
| Simplex | R ohm | 100% | 100% | 50% | 50% | Simplex | R ohm | 100% | 100% | 50% | 50% |
| | X ohm | 100% | 100% | 49% | 51% | | X ohm | 100% | 100% | 49% | 51% |
| | B S | 100% | 100% | 204% | 196% | | B S | 100% | 100% | 204% | 196% |
| Duplex | R ohm | 50% | 50% | 25% | 25% | Duplex | R ohm | 50% | 50% | 25% | 25% |
| | X ohm | 72% | 71% | 35% | 37% | | X ohm | 72% | 72% | 35% | 37% |
| | B S | 138% | 139% | 284% | 269% | | B S | 137% | 137% | 282% | 267% |
| Triplex | R ohm | 33% | 33% | 17% | 17% | Triplex | R ohm | 33% | 33% | 17% | 17% |
| | X ohm | 90% | 89% | 44% | 46% | | X ohm | 91% | 91% | 45% | 47% |
| | B S | 109% | 109% | 223% | 214% | | B S | 107% | 108% | 220% | 210% |

**Table 25: Comparison of different electrical parameters per kilometer for Gull and Cardinal cable types**

| | X/R | | | | |
|---|---|---|---|---|---|
| | Single Circuit | | Double Circuit | | |
| | 1 | 2 | 3 | 4 | Global Average |
| **Simplex** | 100% | 100% | 98% | 102% | **1,00x** |
| **Duplex** | 143% | 143% | 139% | 147% | **1,43x** |
| **Triplex** | 269% | 269% | 264% | 275% | **2,69x** |

**Table 26: X/R multiples averaged for all cable types**

## 9.2. X/R relationships

### 9.2.1. 220 kV

### Austria

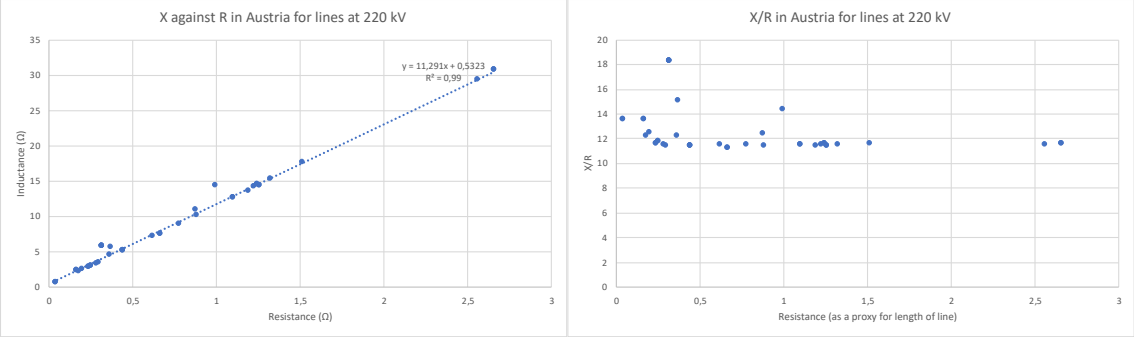



Figure 82: Relation summary between X and R in lines at 220 kV in Austria

### Belgium

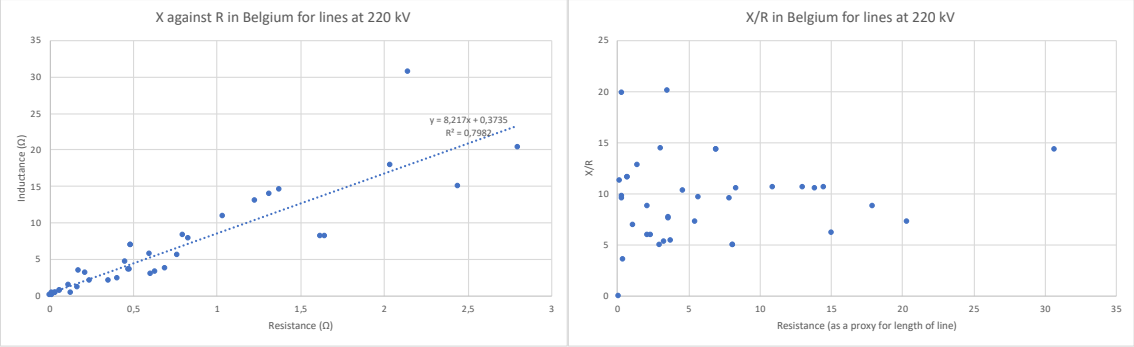



**Figure 83: Relation summary between X and R in lines at 220 kV in Belgium**

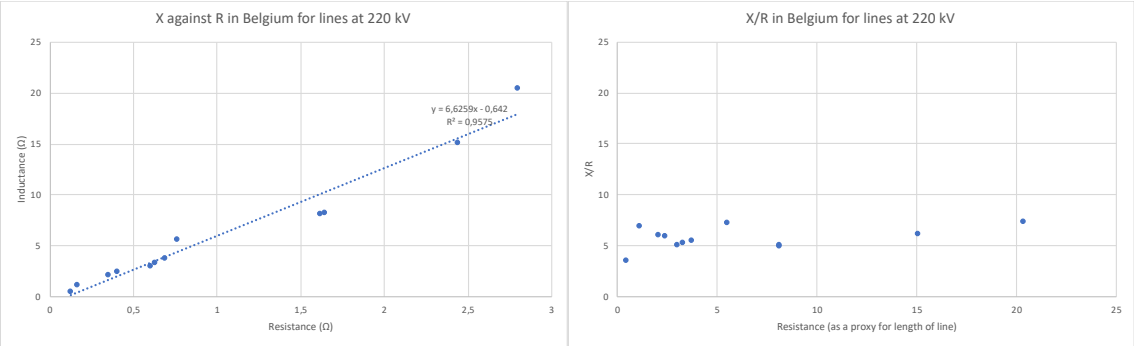



**Figure 84: Relation 1 between X and R in lines at 220 kV in Belgium**

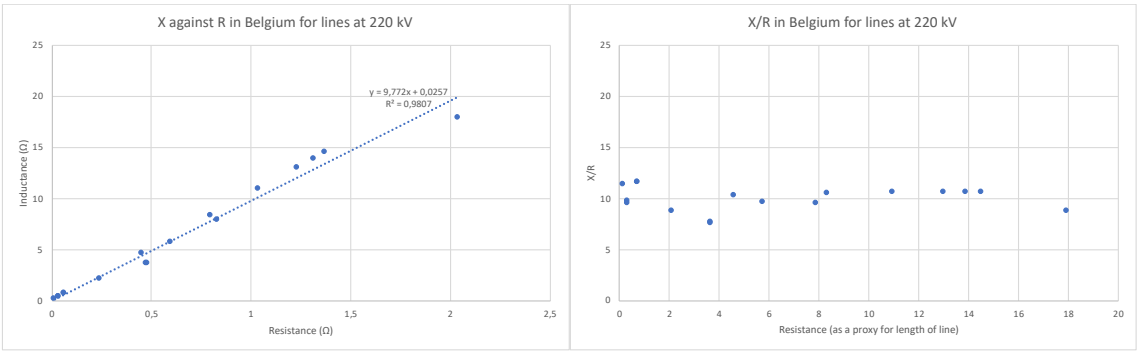



**Figure 85: Relation 2 between X and R in lines at 220 kV in Belgium**

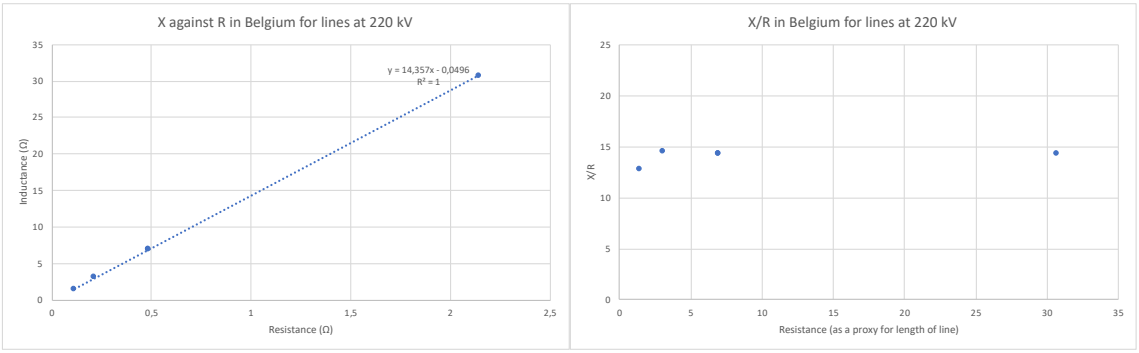



**Figure 86: Relation 3 between X and R in lines at 220 kV in Belgium**

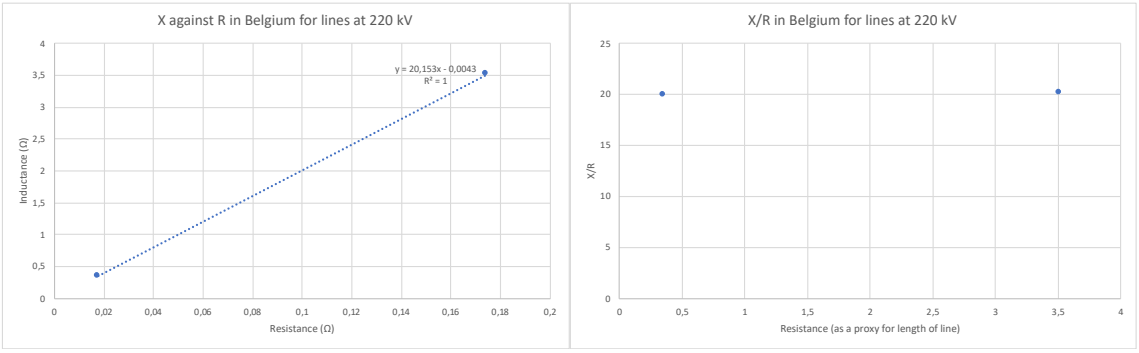



**Figure 87: Relation 4 between X and R in lines at 220 kV in Belgium**

## Bulgaria

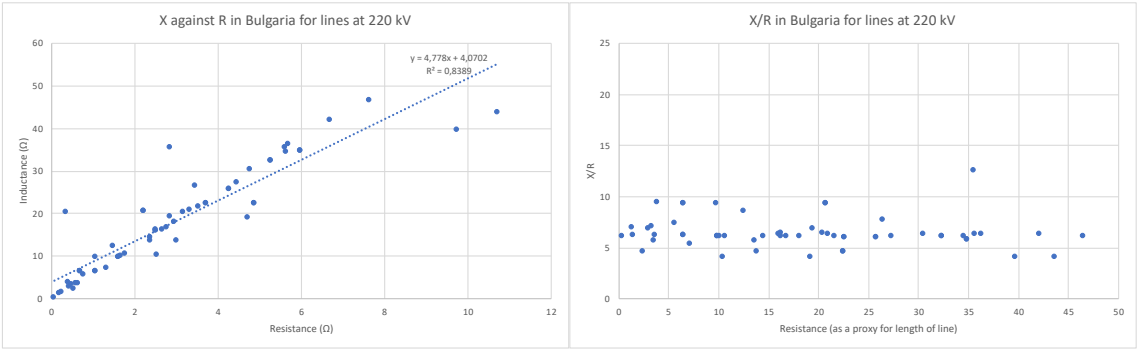



**Figure 88: Relation summary between X and R in lines at 220 kV in Bulgaria**

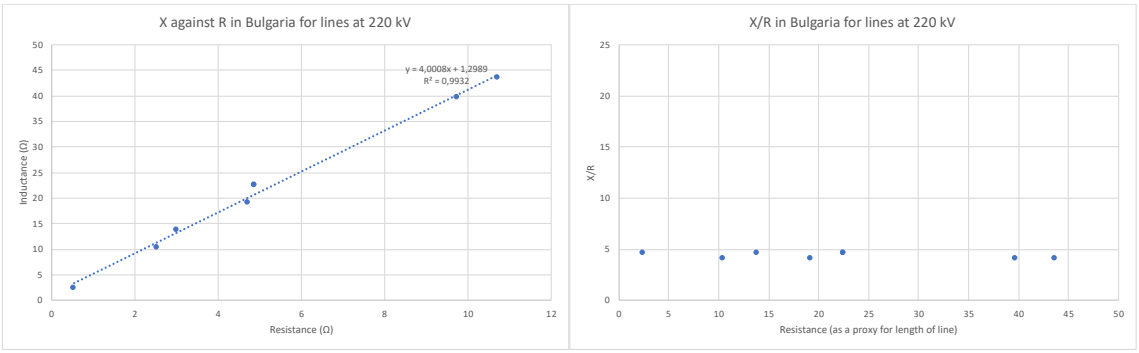



**Figure 89: Relation 1 between X and R in lines at 220 kV in Bulgaria**

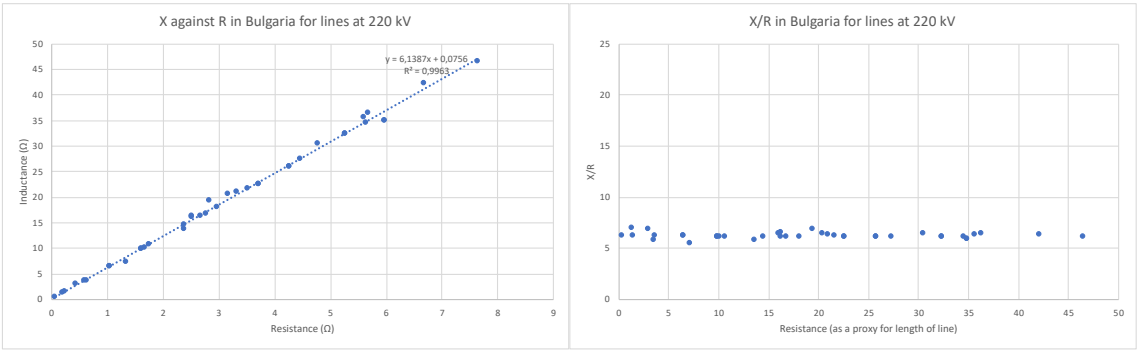



**Figure 90: Relation 2 between X and R in lines at 220 kV in Bulgaria**

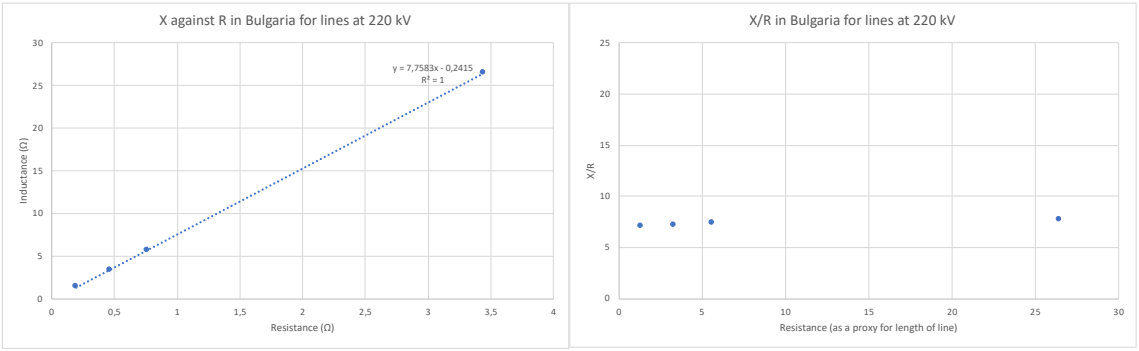



**Figure 91: Relation 3 between X and R in lines at 220 kV in Bulgaria**

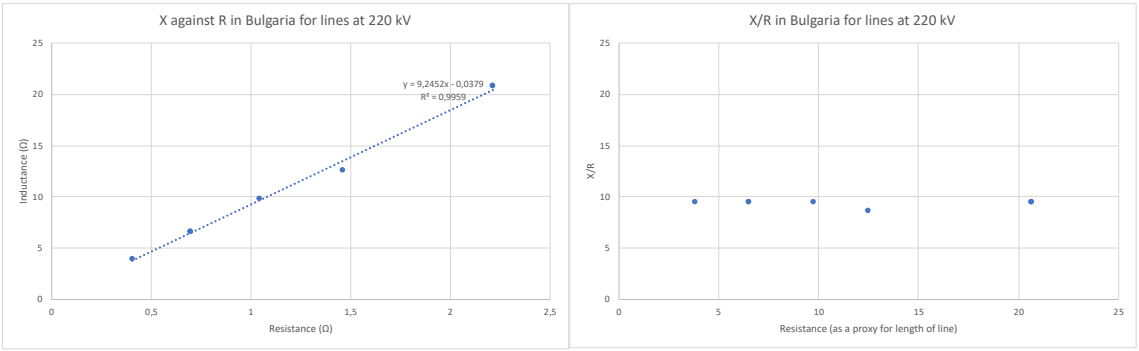



**Figure 92: Relation 4 between X and R in lines at 220 kV in Bulgaria**

## Switzerland

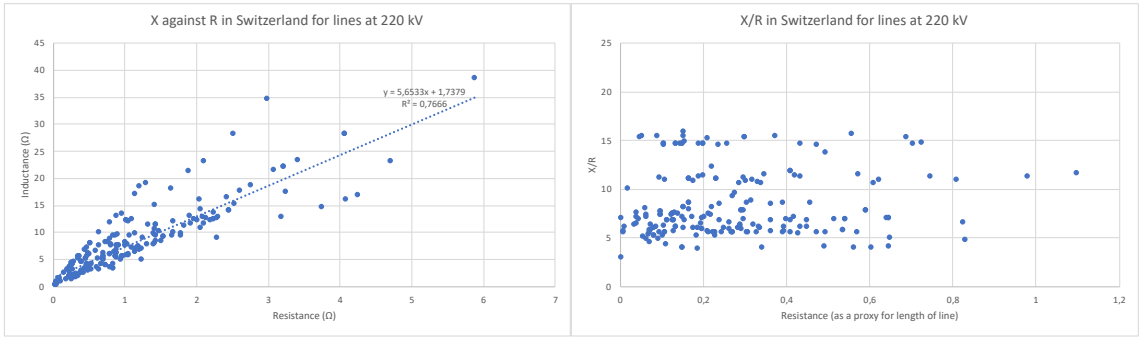



**Figure 93: Relation summary between X and R in lines at 220 kV in Switzerland**

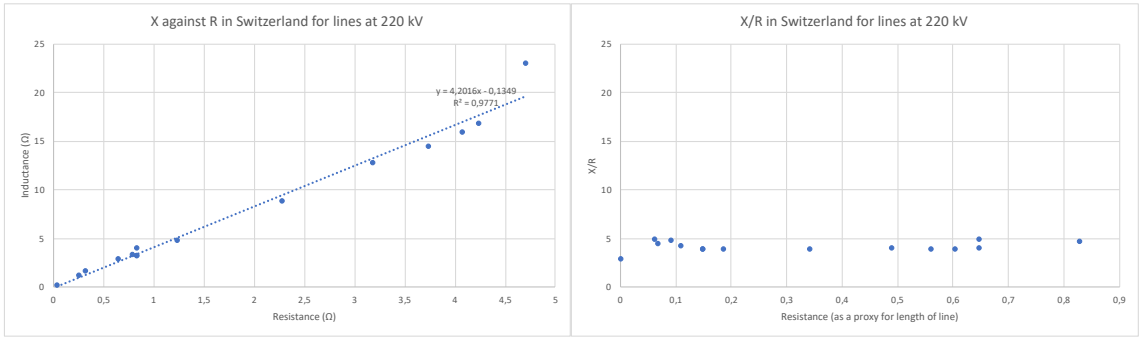



**Figure 94: Relation 1 between X and R in lines at 220 kV in Switzerland**

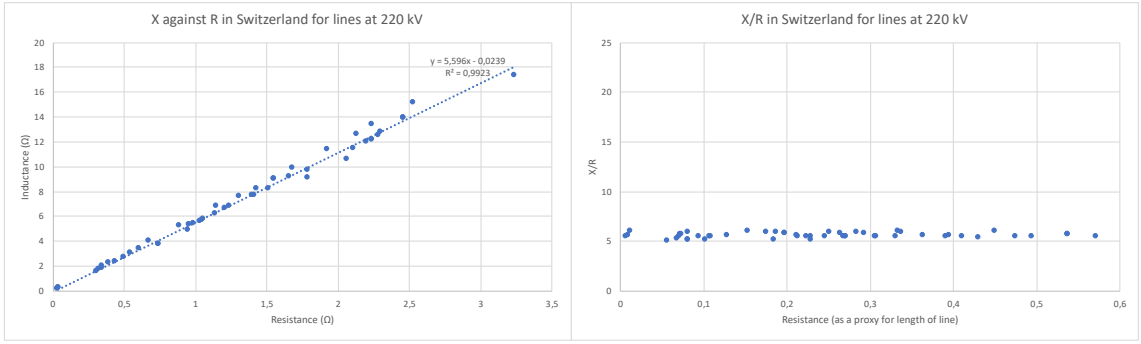



**Figure 95: Relation 2 between X and R in lines at 220 kV in Switzerland**

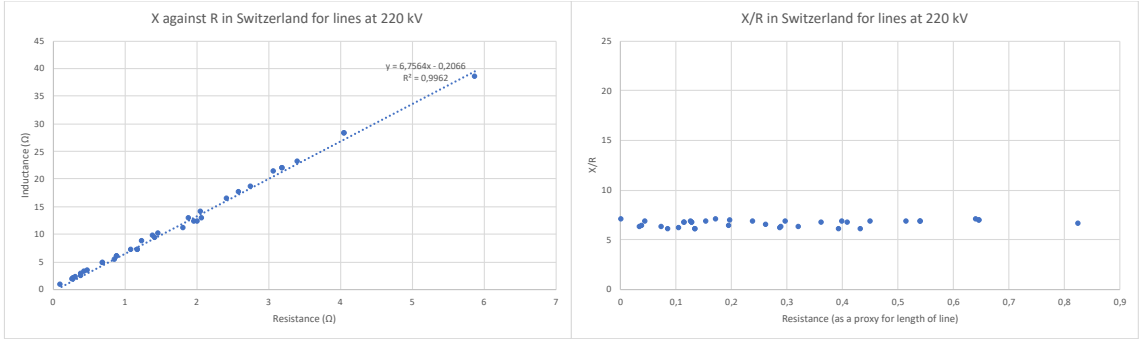



**Figure 96: Relation 3 between X and R in lines at 220 kV in Switzerland**

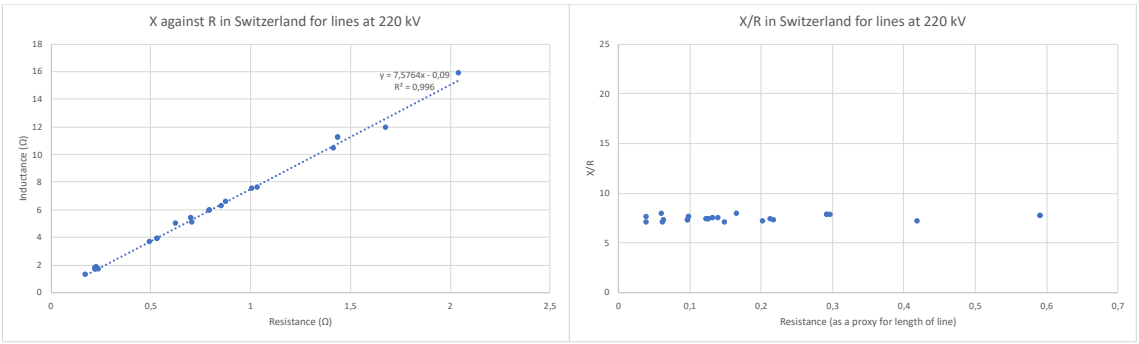



**Figure 97: Relation 4 between X and R in lines at 220 kV in Switzerland**

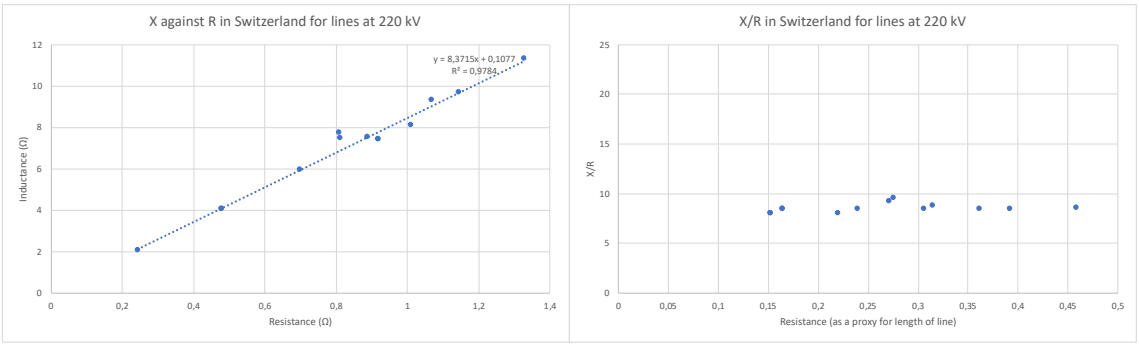



**Figure 98: Relation 5 between X and R in lines at 220 kV in Switzerland**

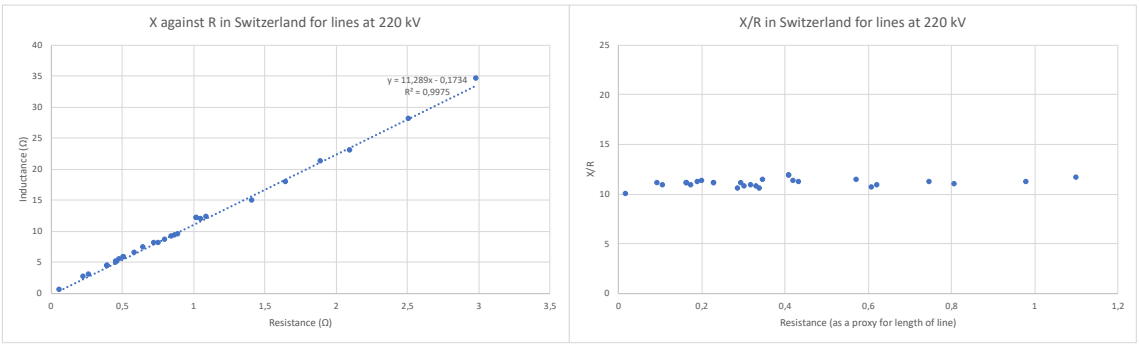



**Figure 99: Relation 6 between X and R in lines at 220 kV in Switzerland**

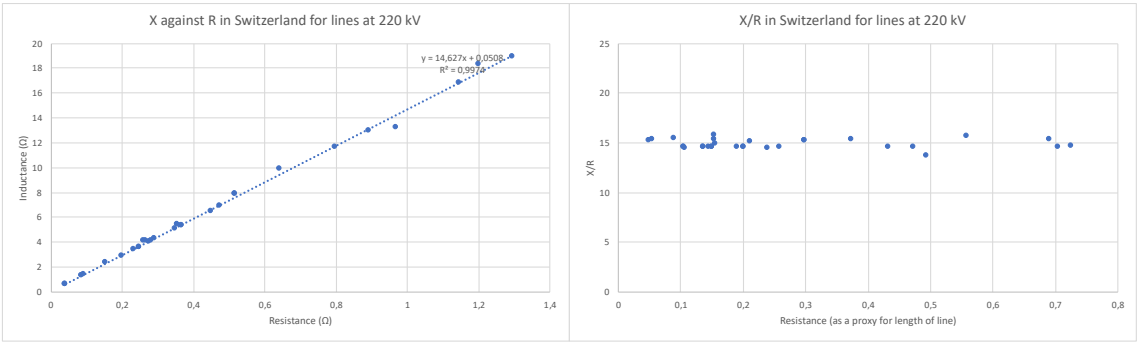



**Figure 100: Relation 7 between X and R in lines at 220 kV in Switzerland**

## Germany

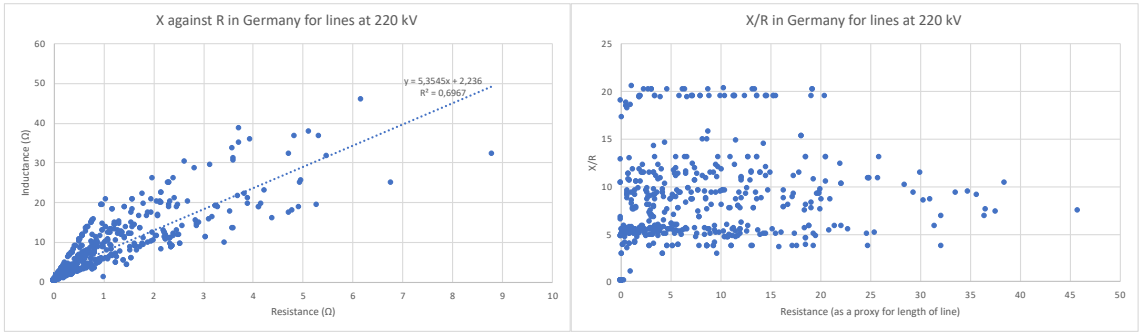



**Figure 101: Relation summary between X and R in lines at 220 kV in Germany**

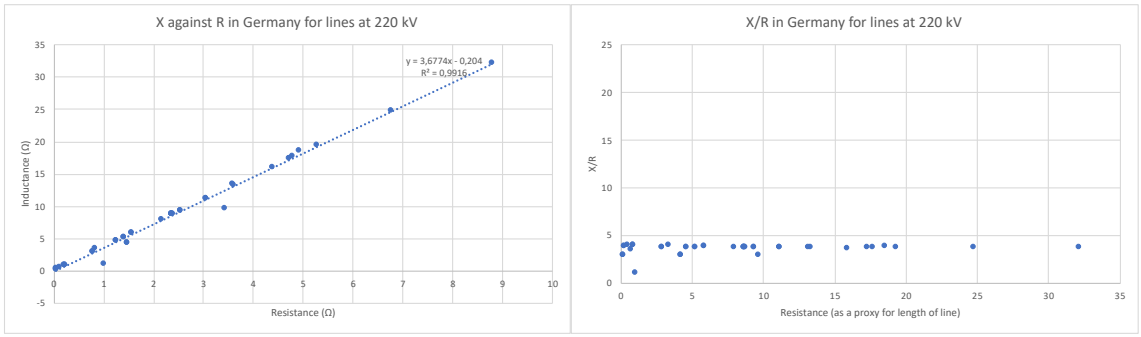



**Figure 102: Relation 1 between X and R in lines at 220 kV in Germany**

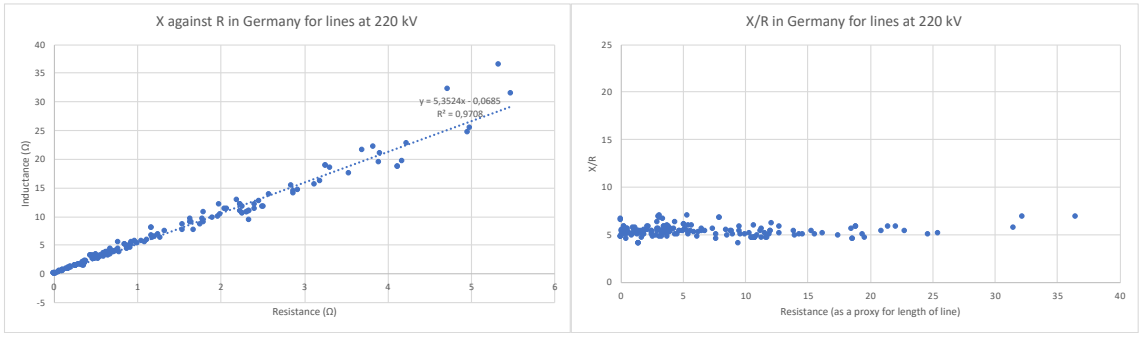



**Figure 103: Relation 2 between X and R in lines at 220 kV in Germany**

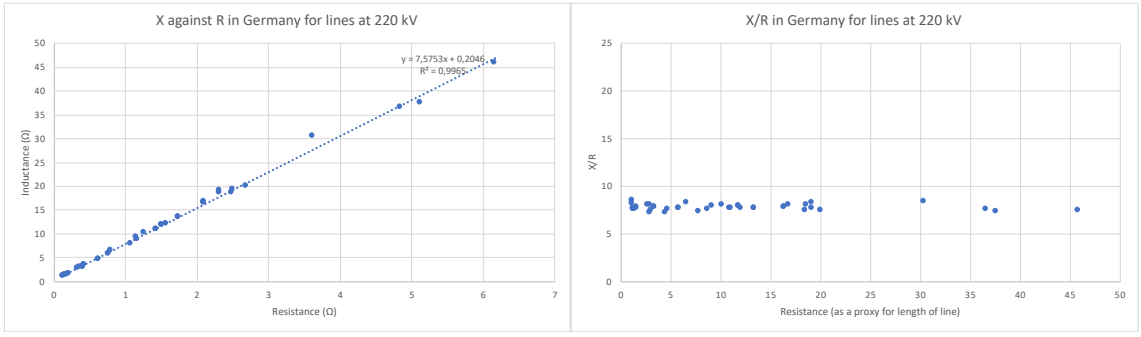



**Figure 104: Relation 3 between X and R in lines at 220 kV in Germany**

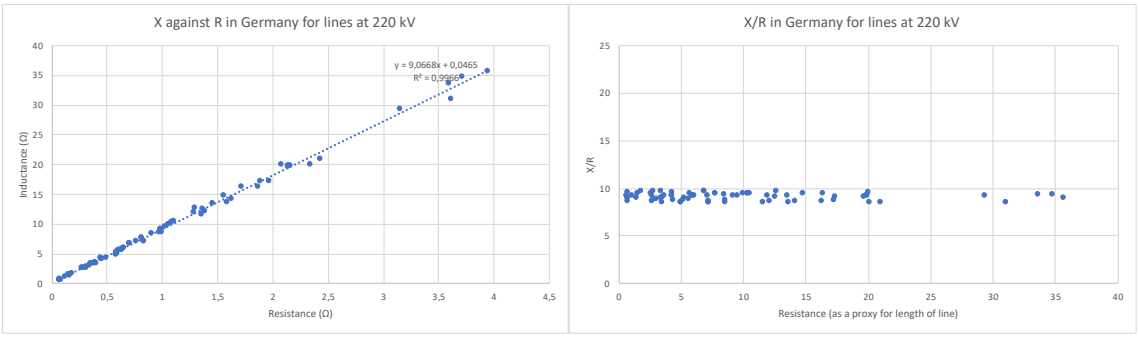



**Figure 105: Relation 4 between X and R in lines at 220 kV in Germany**

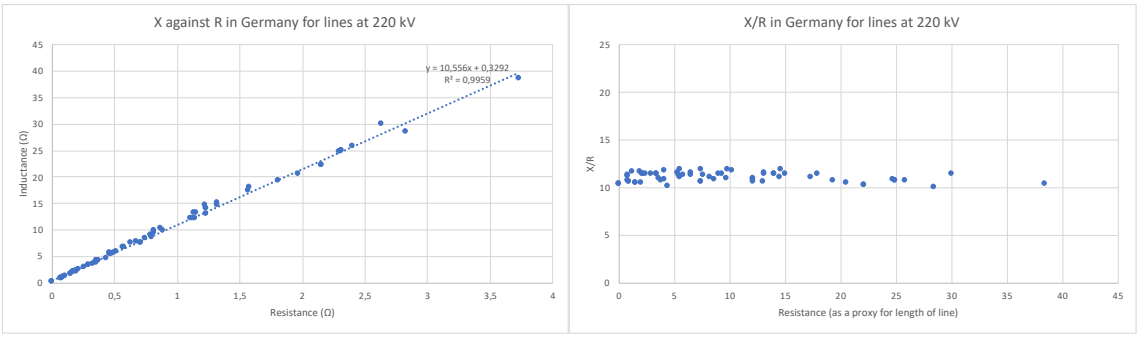



**Figure 106: Relation 5 between X and R in lines at 220 kV in Germany**

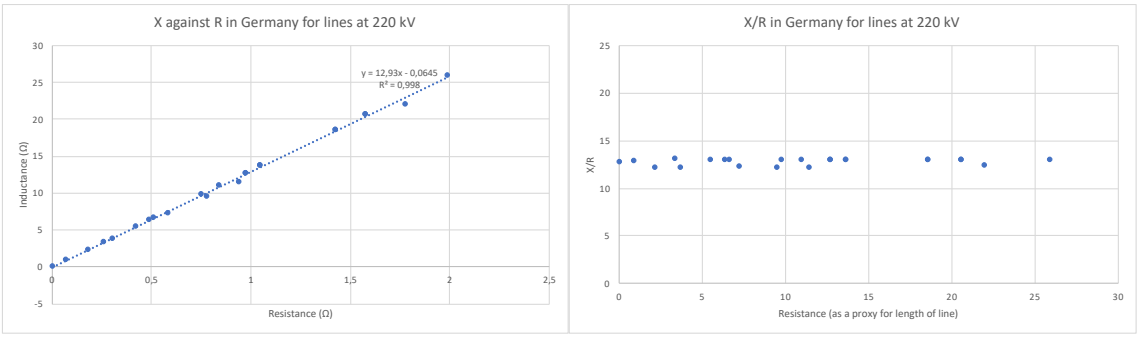



**Figure 107: Relation 6 between X and R in lines at 220 kV in Germany**

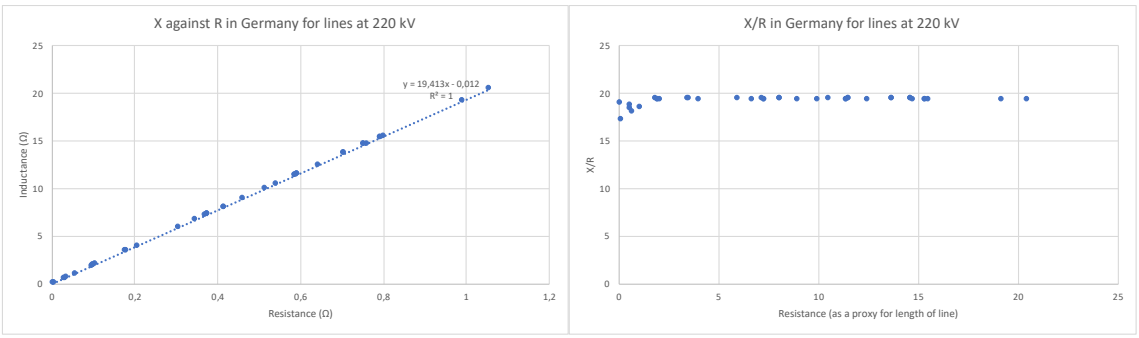



**Figure 108: Relation 7 between X and R in lines at 220 kV in Germany**

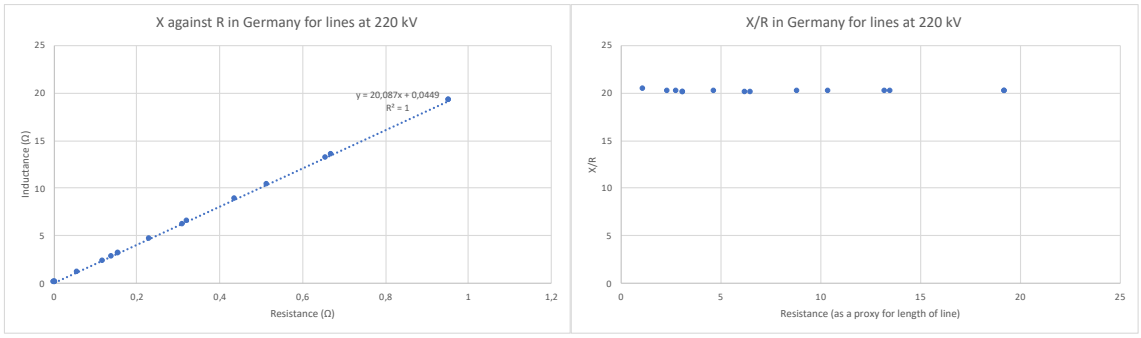



**Figure 109: Relation 8 between X and R in lines at 220 kV in Germany**

## Denmark

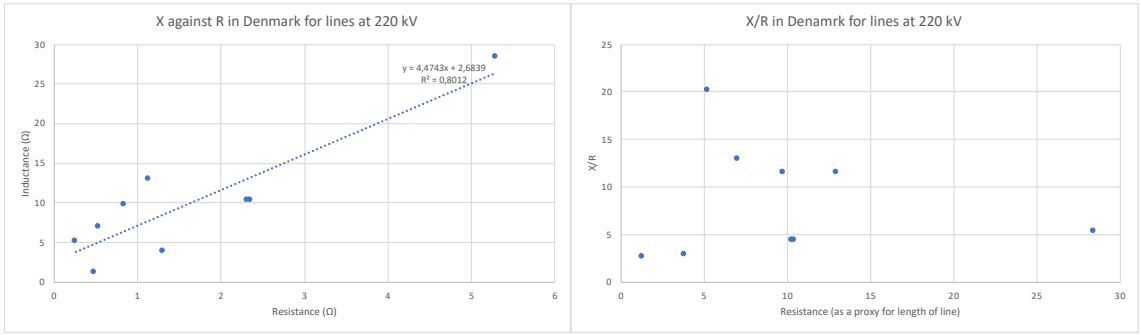



**Figure 110: Relation summary between X and R in lines at 200 kV in Denmark**

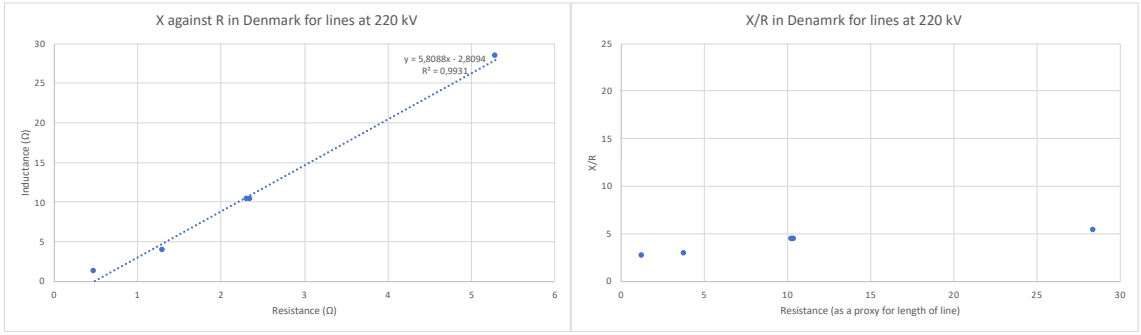



**Figure 111: Relation 1 between X and R in lines at 220 kV in Denmark**

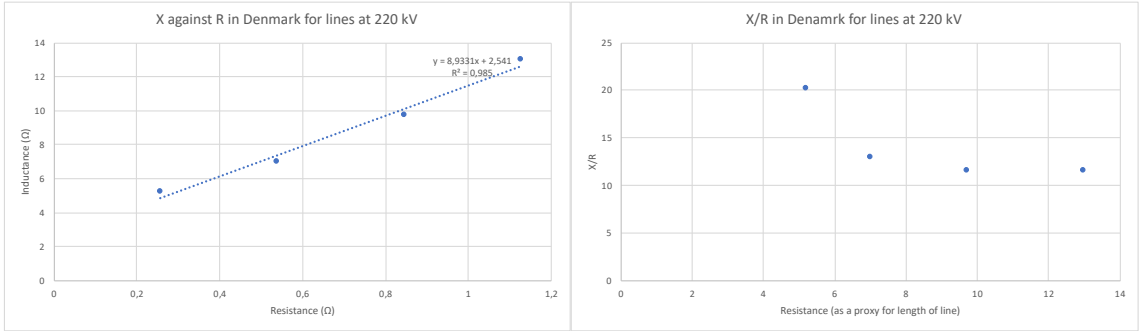



**Figure 112: Relation 2 between X and R in lines at 220 kV in Denmark**

## Spain

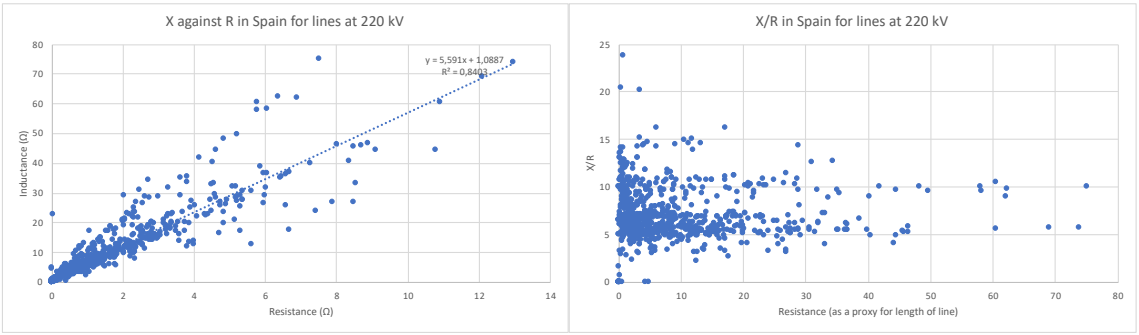



**Figure 113: Relation summary between X and R in lines at 220 kV in Spain**

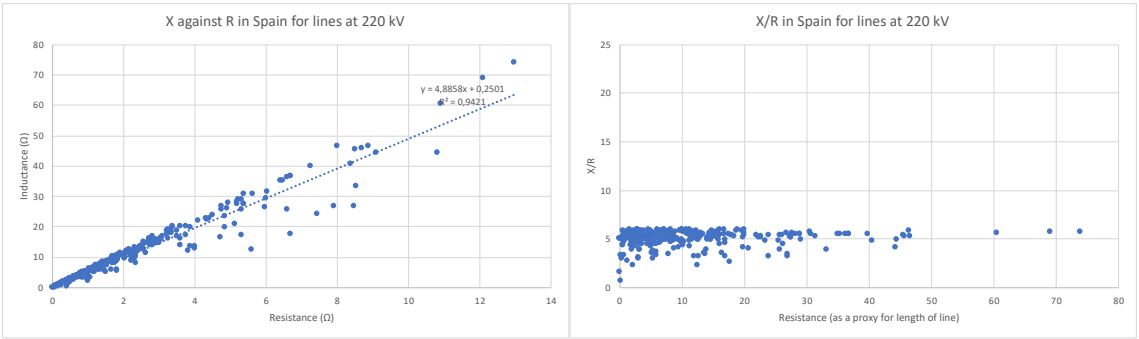



**Figure 114: Relation 1 between X and R in lines at 220 kV in Spain**

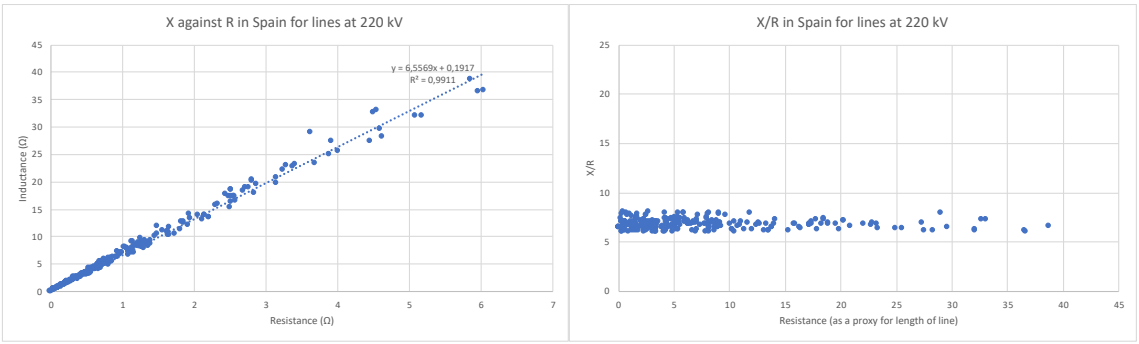



**Figure 115: Relation 2 between X and R in lines at 220 kV in Spain**

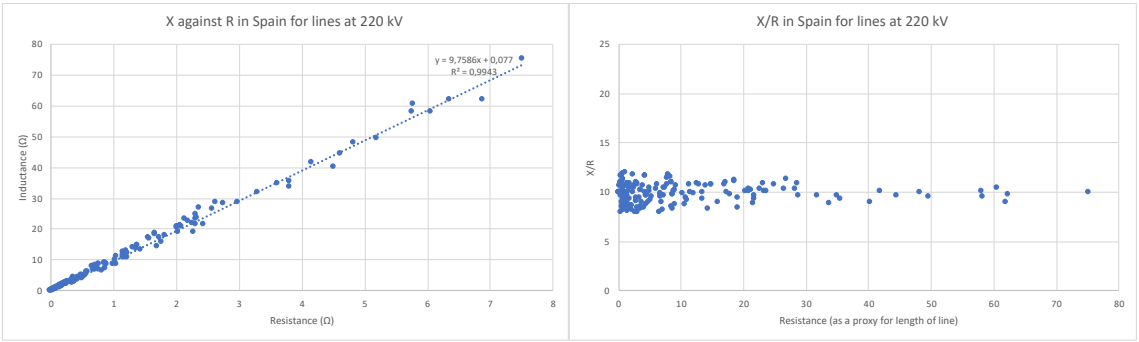



**Figure 116: Relation 3 between X and R in lines at 220 kV in Spain**

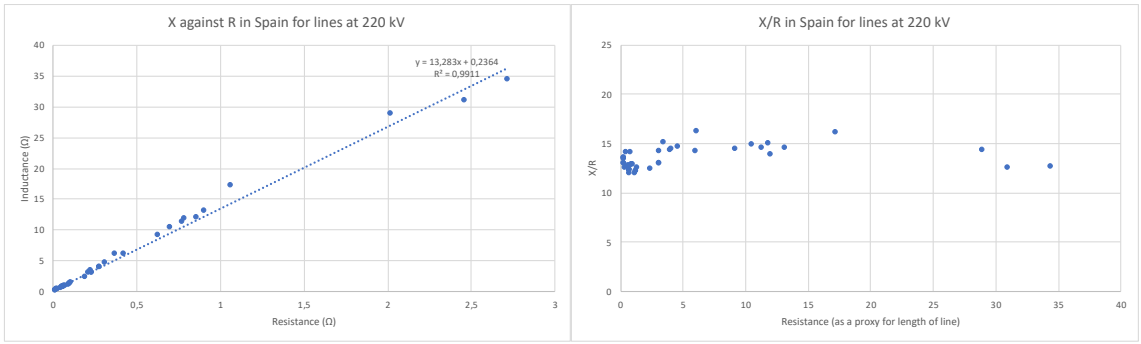



**Figure 117: Relation 4 between X and R in lines at 220 kV in Spain**

## France

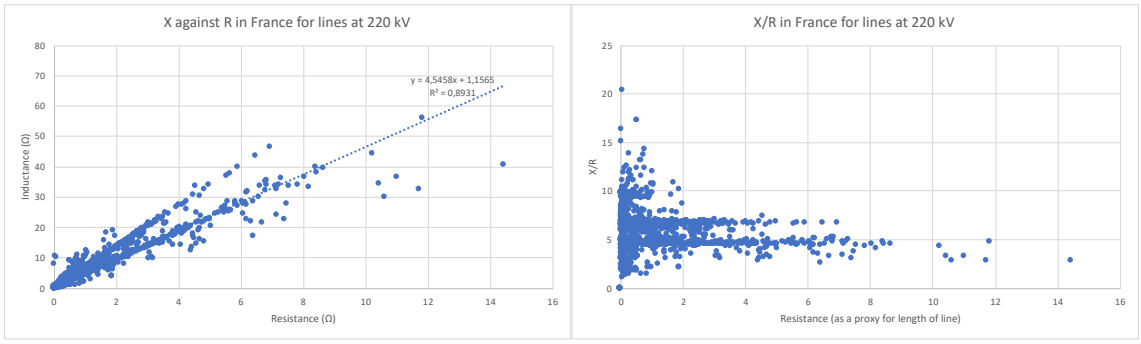



**Figure 118: Relation summary between X and R in lines at 220 kV in France**

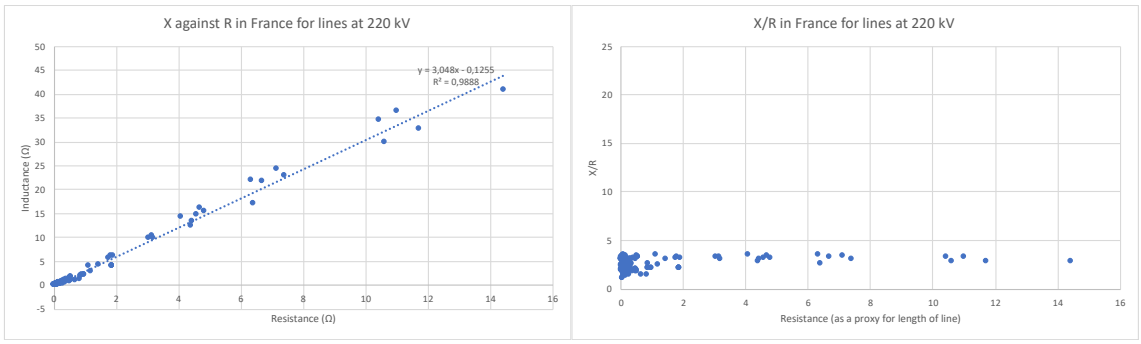



**Figure 119: Relation 1 between X and R in lines at 220 kV in France**

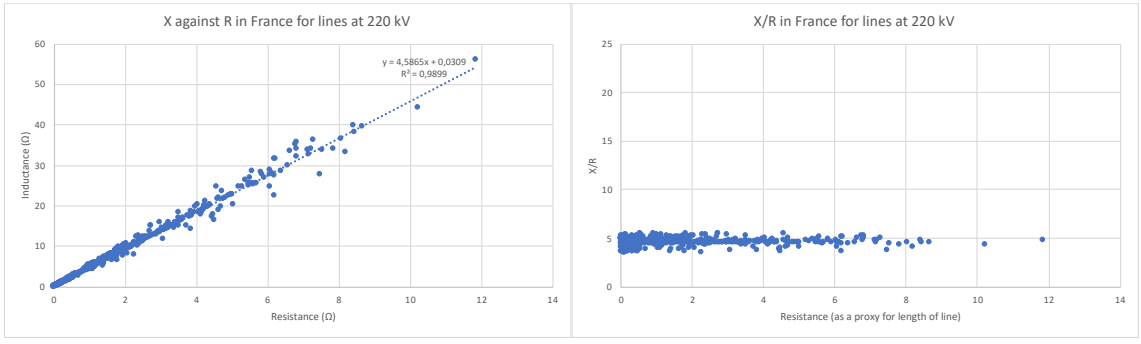



**Figure 120: Relation 2 between X and R in lines at 220 kV in France**

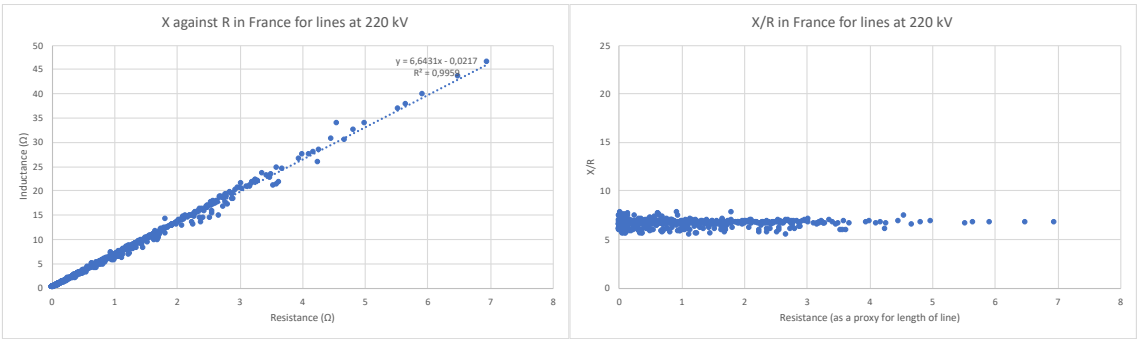



**Figure 121: Relation 3 between X and R in lines at 220 kV in France**

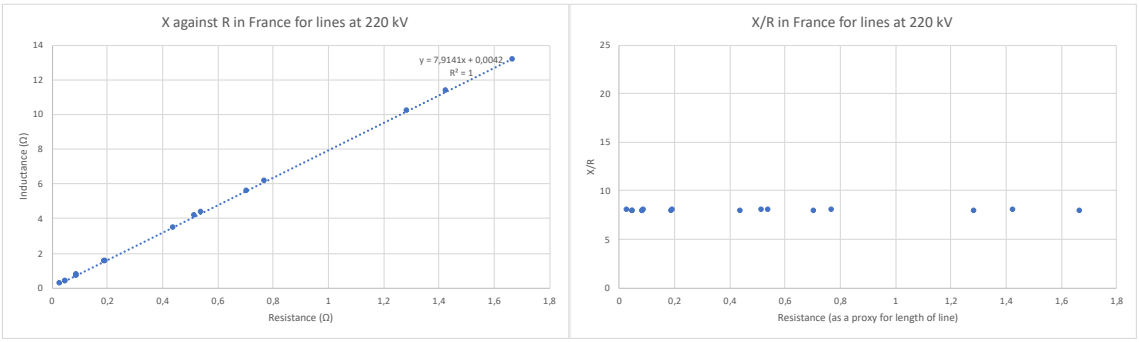



**Figure 122: Relation 4 between X and R in lines at 220 kV in France**

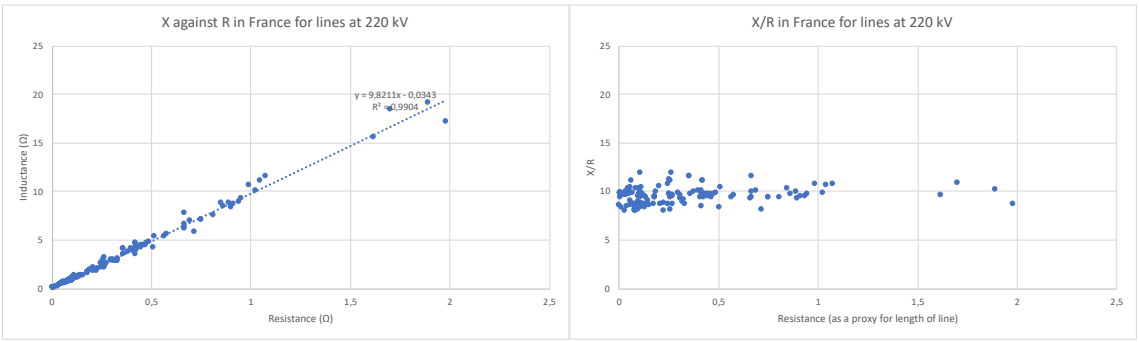



**Figure 123: Relation 5 between X and R in lines at 220 kV in France**

## Hungary

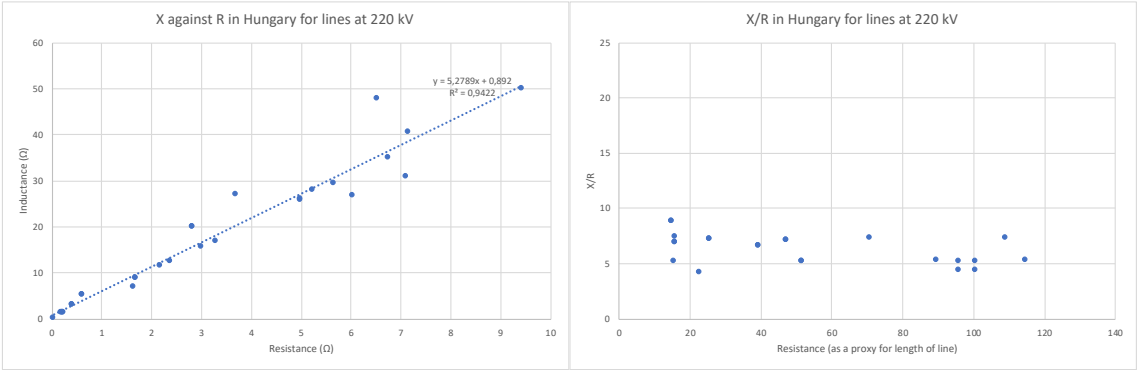



**Figure 124: Relation summary between X and R in lines at 220 kV in Hungary**

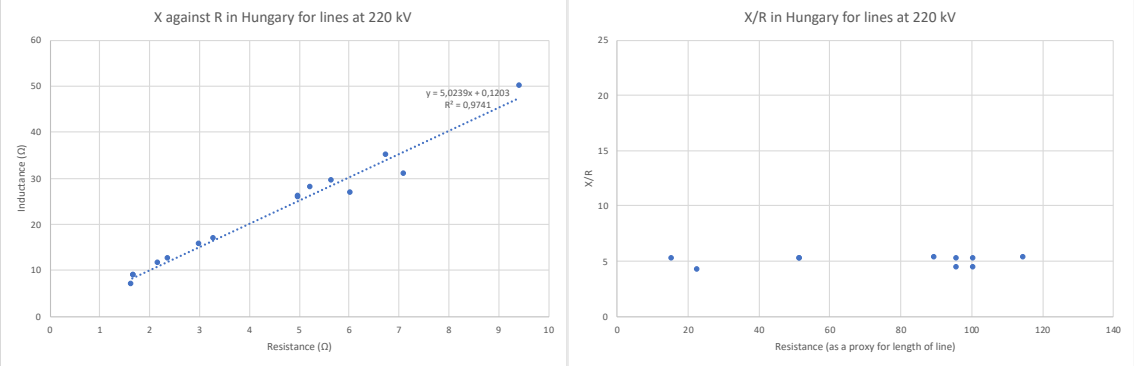



**Figure 125: Relation 1 between X and R in lines at 220 kV in Hungary**

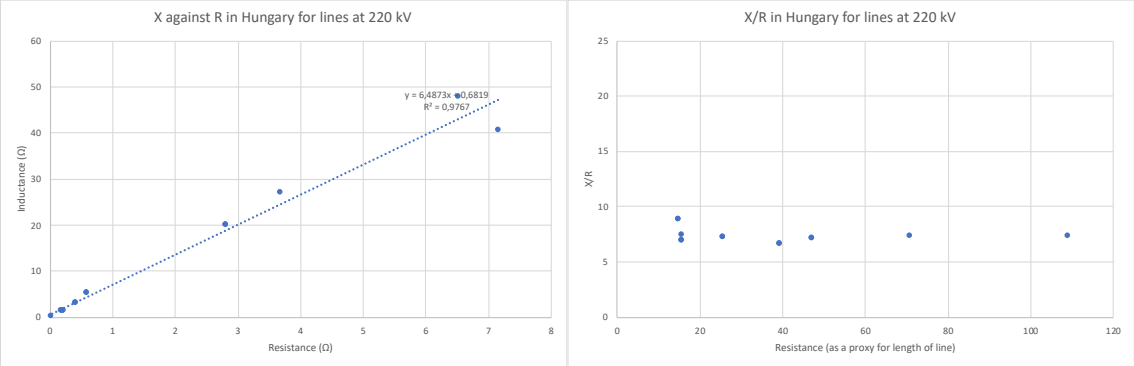



**Figure 126: Relation 2 between X and R in lines at 220 kV in Hungary**

## Italy

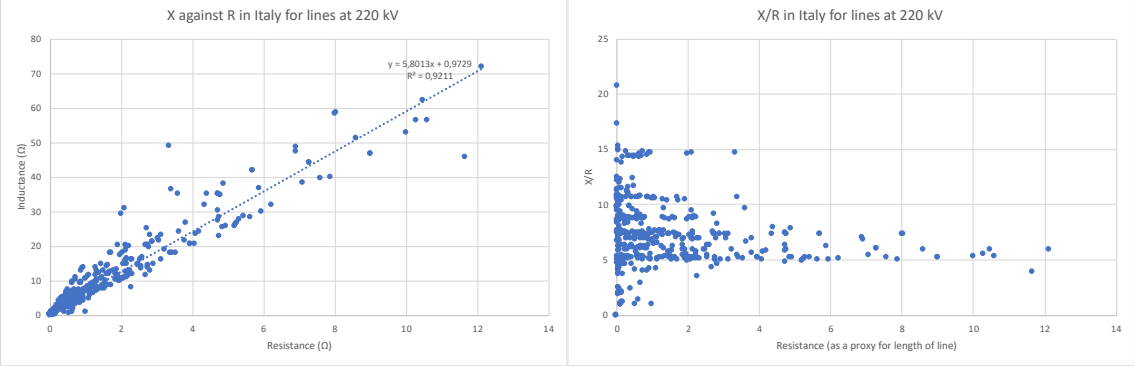



**Figure 127: Relation summary between X and R in lines at 220 kV in Italy**

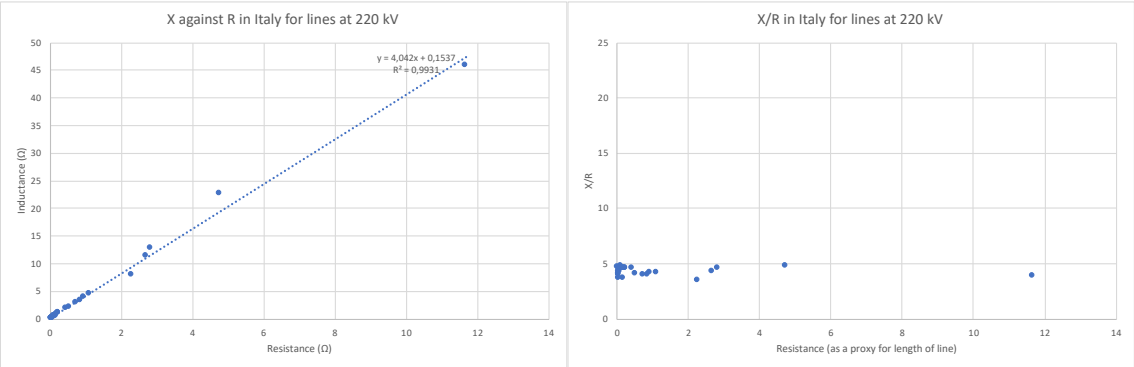



**Figure 128: Relation 1 between X and R in lines at 220 kV in Italy**

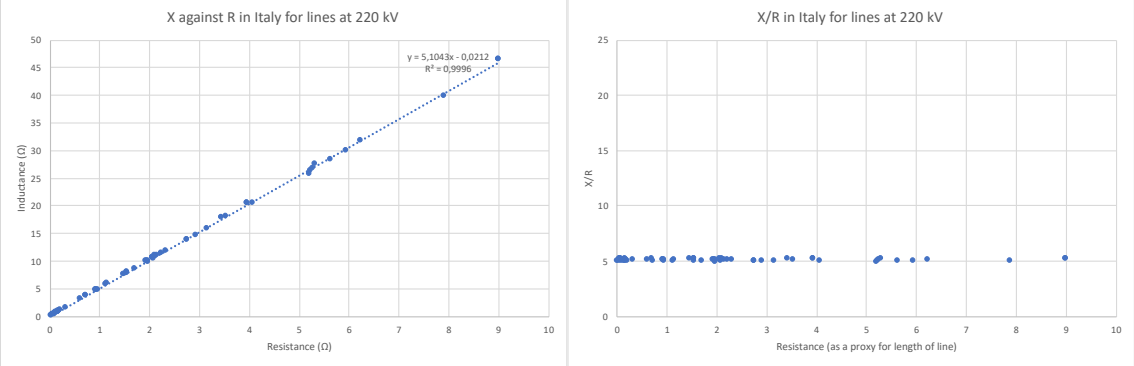



**Figure 129: Relation 2 between X and R in lines at 220 kV in Italy**

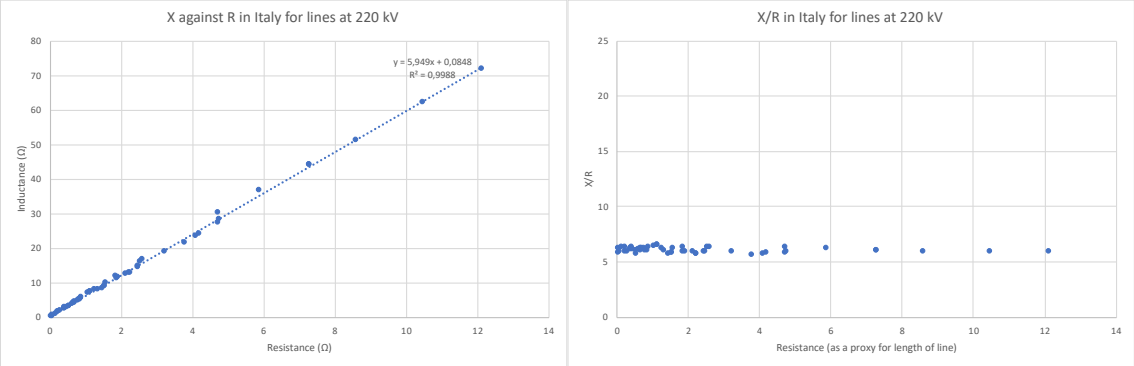



**Figure 130: Relation 3 between X and R in lines at 220 kV in Italy**

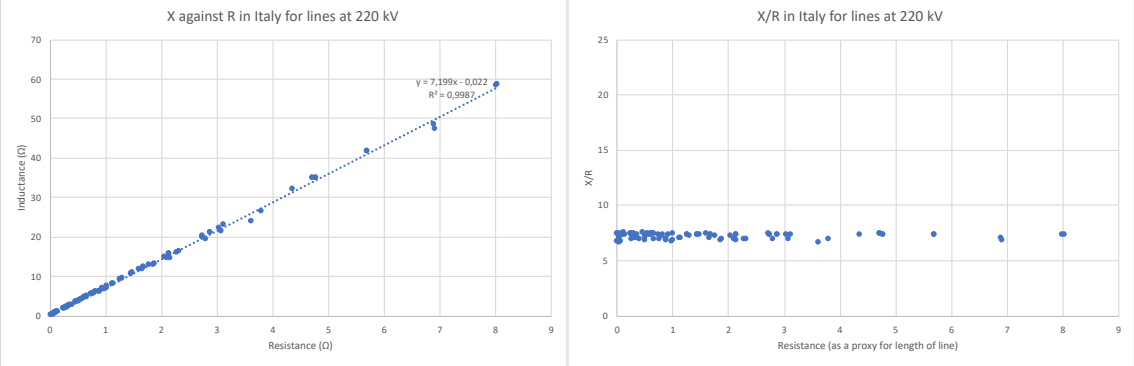



**Figure 131: Relation 4 between X and R in lines at 220 kV in Italy**

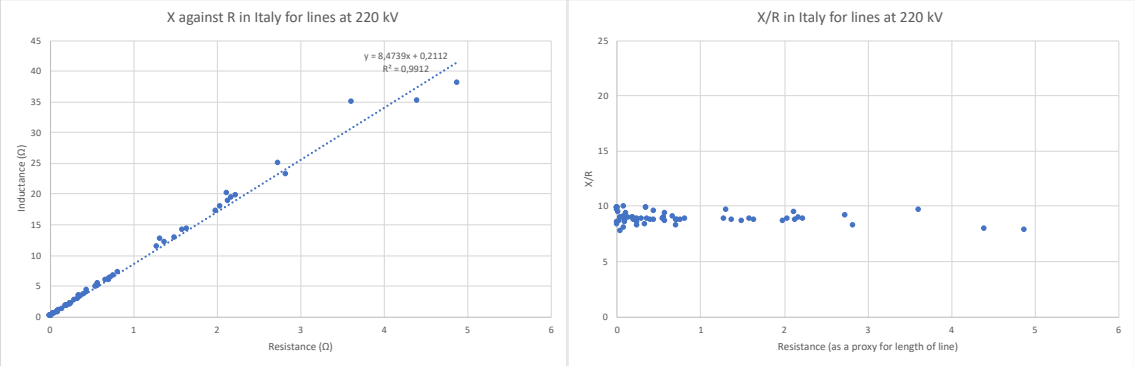



**Figure 132: Relation 5 between X and R in lines at 220 kV in Italy**

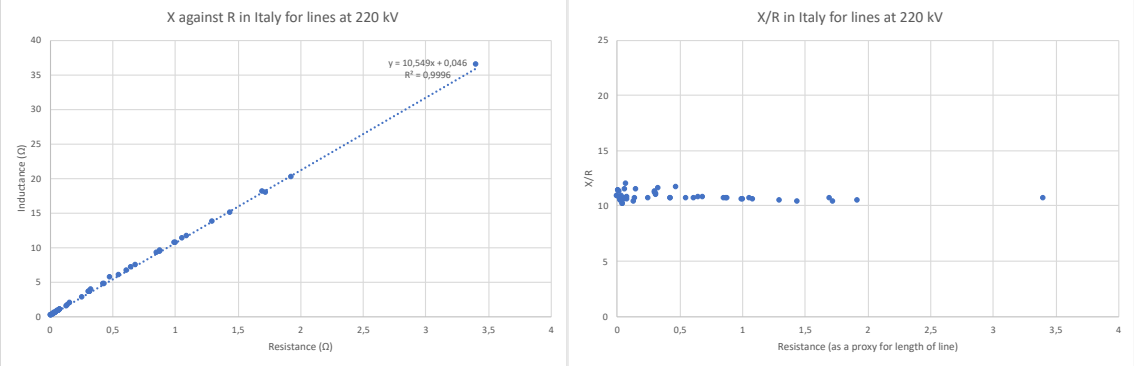



**Figure 133: Relation 6 between X and R in lines at 220 kV in Italy**

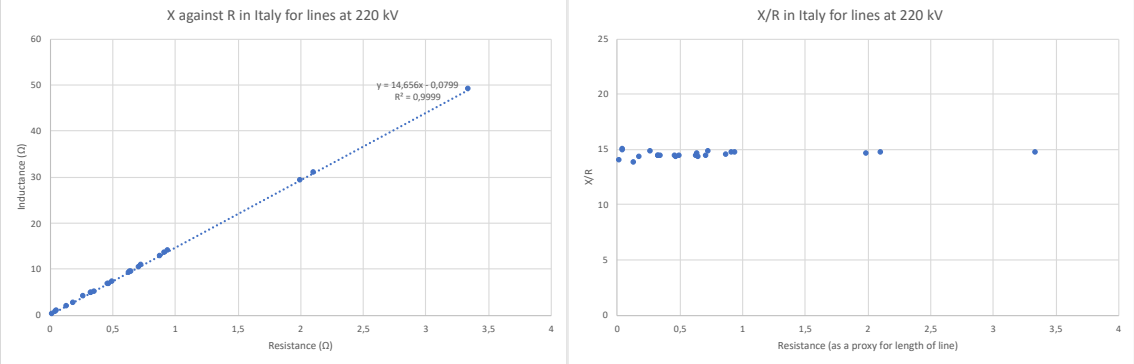



**Figure 134: Relation 7 between X and R in lines at 220 kV in Italy**

## Netherlands

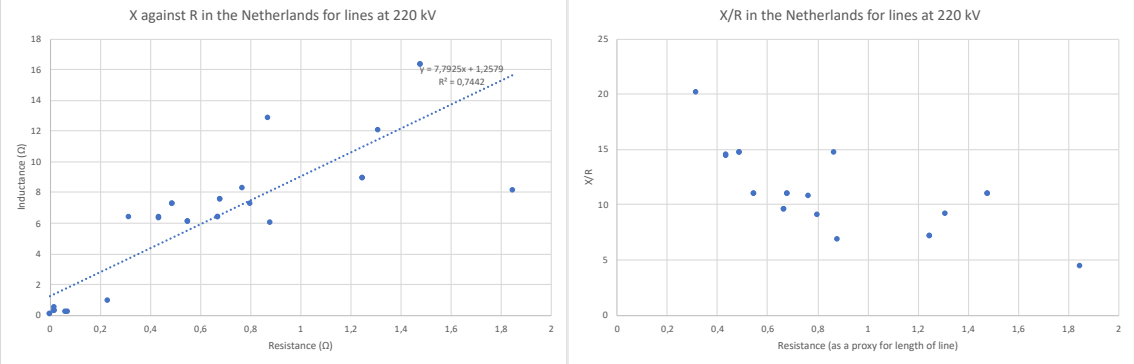



**Figure 135: Relation summary between X and R in lines at 220 kV in the Netherlands**

## Poland

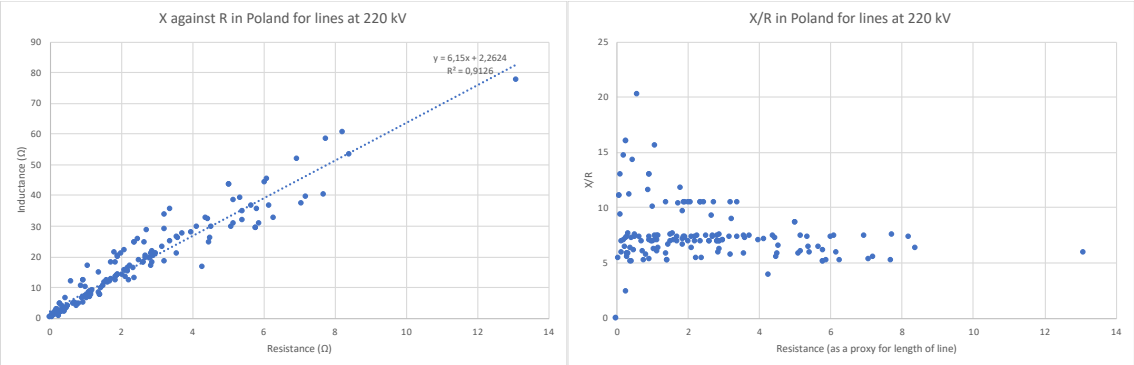


**Figure 136: Relation summary between X and R in lines at 220 kV in Poland**

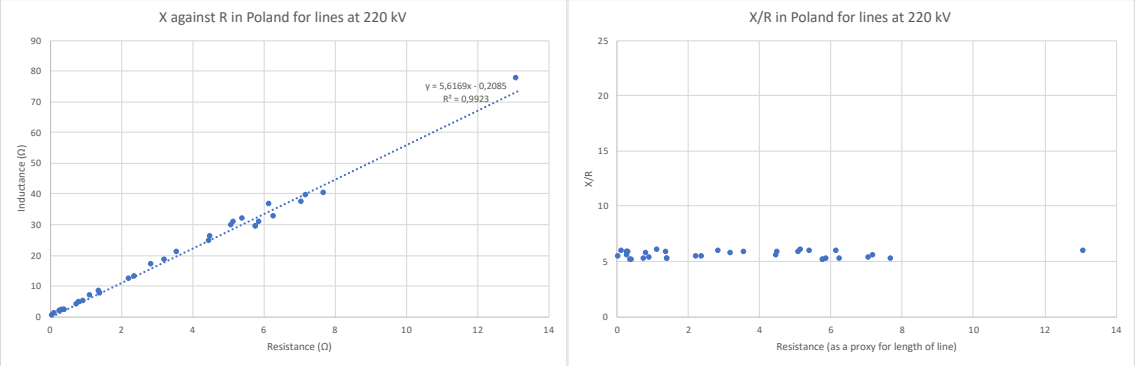



**Figure 137: Relation 1 between X and R in lines at 220 kV in Poland**

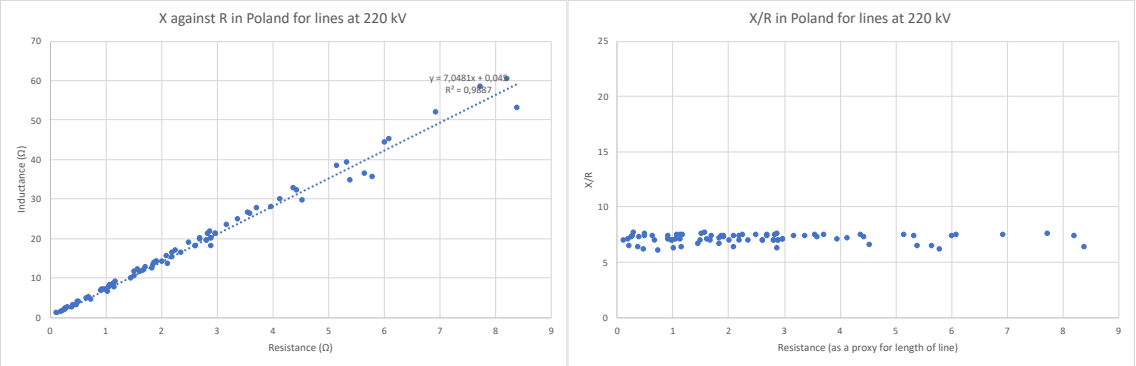



**Figure 138: Relation 2 between X and R in lines at 220 kV in Poland**

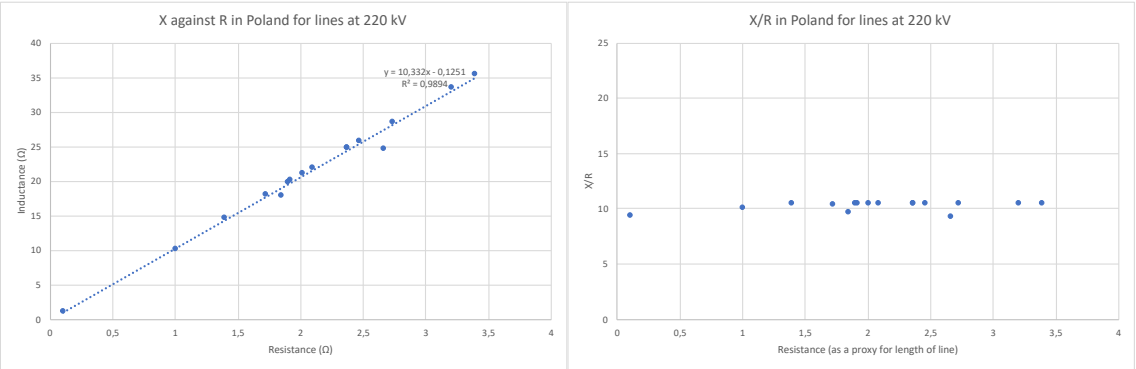



**Figure 139: Relation 3 between X and R in lines at 220 kV in Poland**

# Portugal

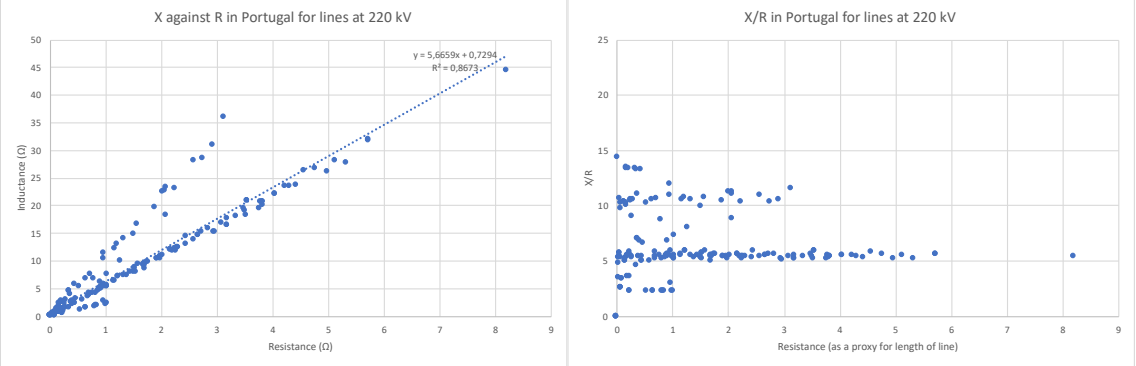


**Figure 140: Relation summary between X and R in lines at 220 kV in Portugal**

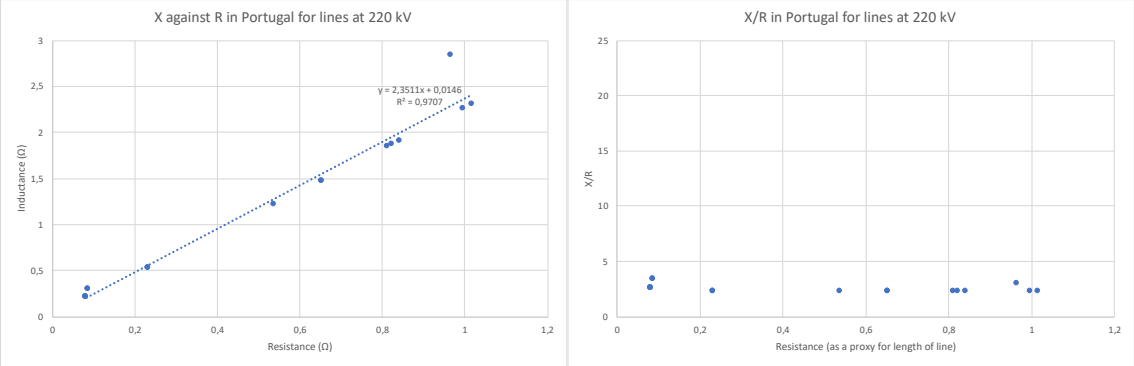



**Figure 141: Relation 1 between X and R in lines at 220 kV in Portugal**

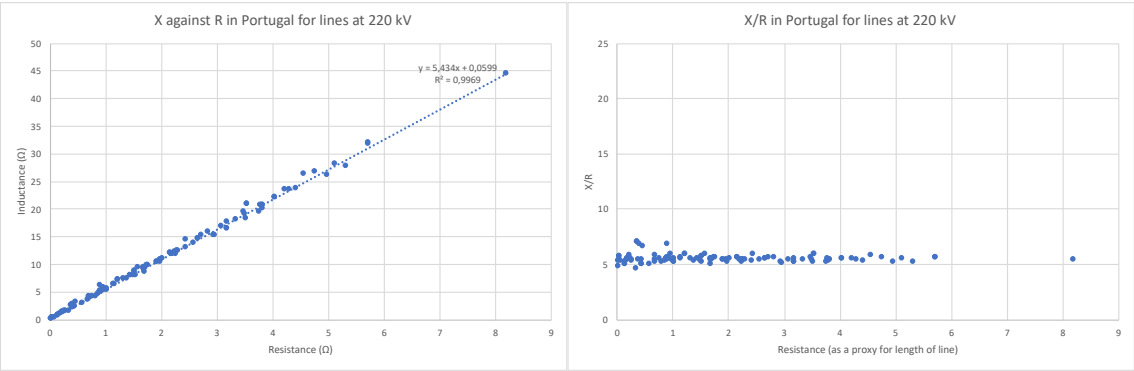



**Figure 142: Relation 2 between X and R in lines at 220 kV in Portugal**

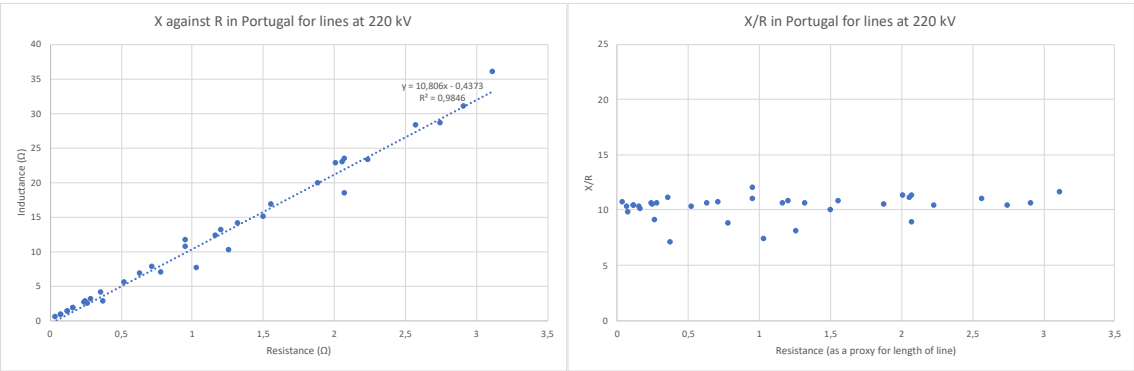



**Figure 143: Relation 3 between X and R in lines at 220 kV in Portugal**

# Romania

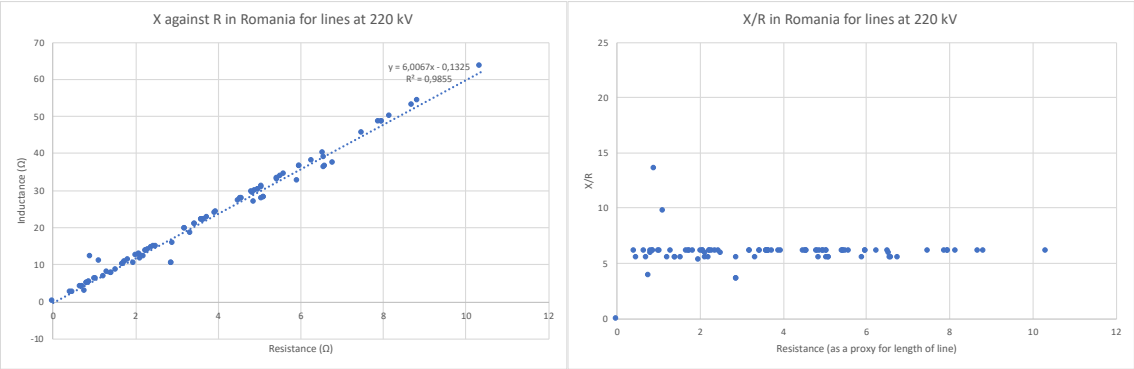



**Figure 144: Relation summary between X and R in lines at 220 kV in Romania**

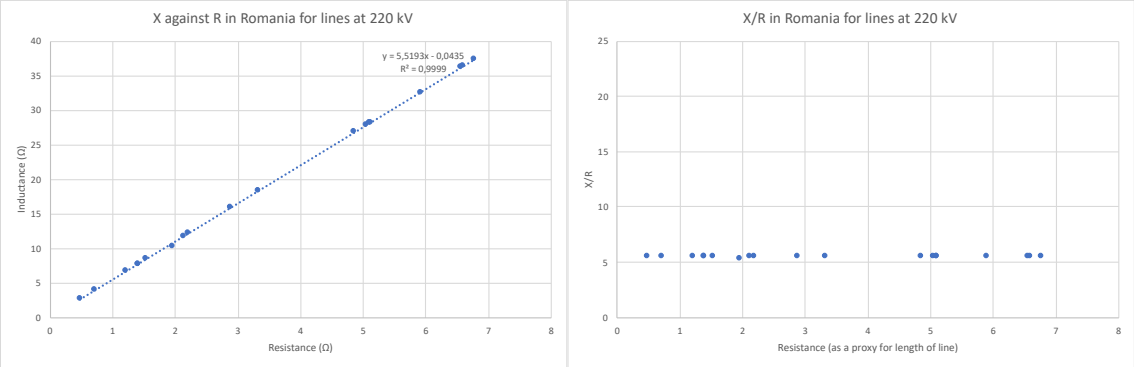



**Figure 145: Relation 1 between X and R in lines at 220 kV in Romania**

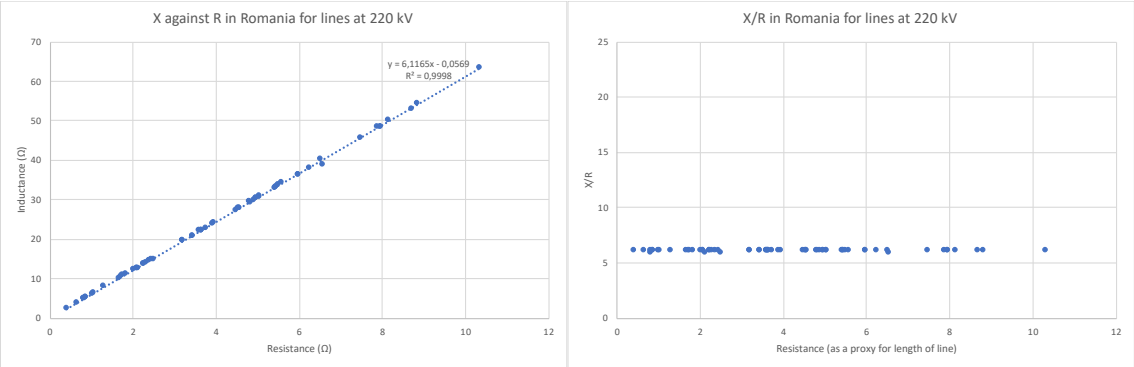



**Figure 146: Relation 2 between X and R in lines at 220 kV in Romania**

## Russia

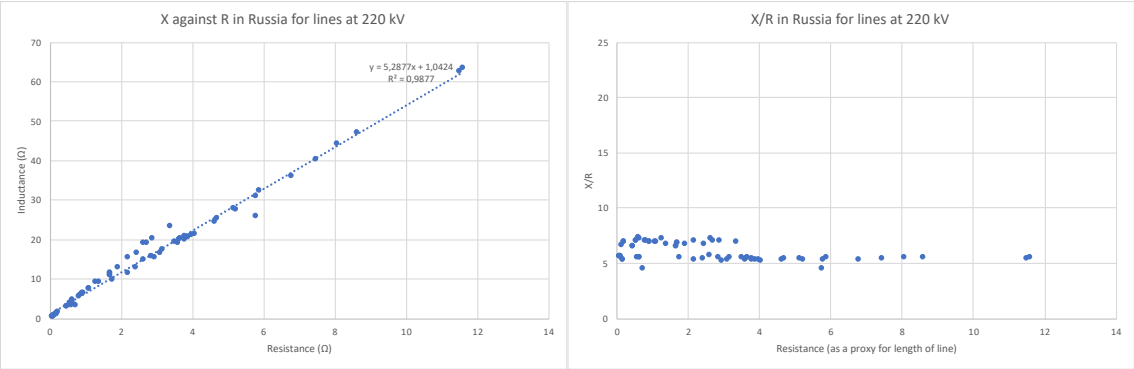



**Figure 147: Relation summary between X and R in lines at 220 kV in Russia**

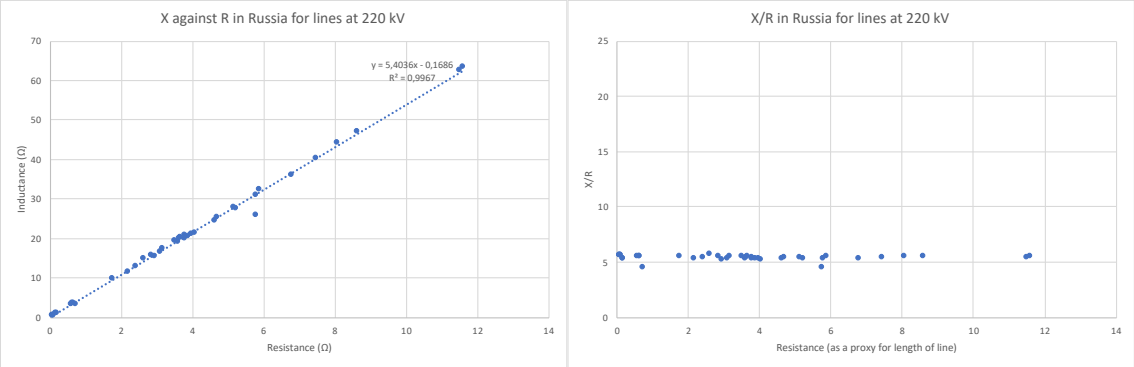



**Figure 148: Relation 1 between X and R in lines at 220 kV in Russia**

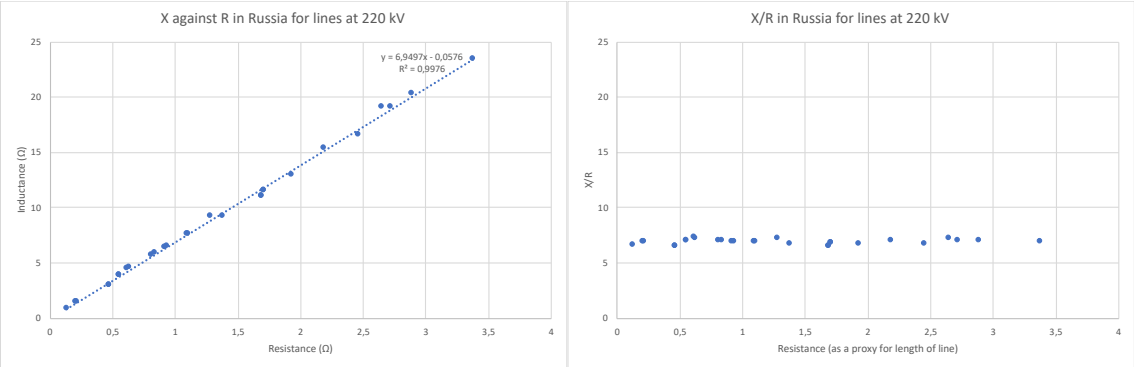



**Figure 149: Relation 2 between X and R in lines at 220 kV in Russia**

### 9.2.2. 400 kV

## Austria

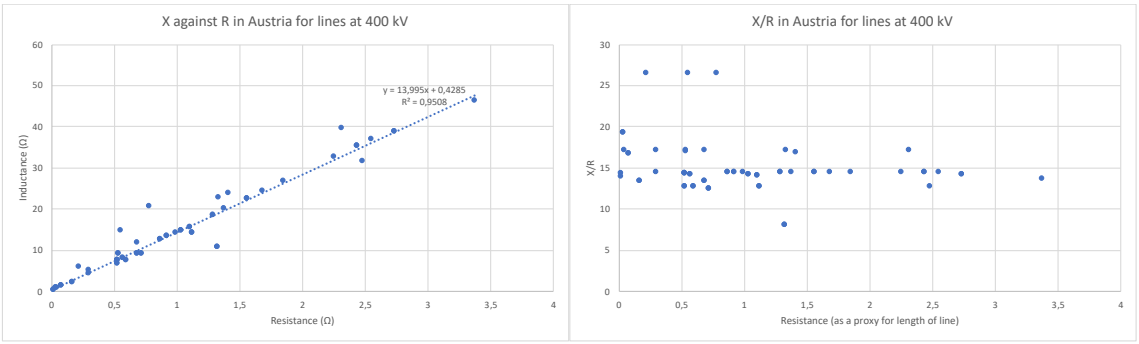



**Figure** Error!**: Relation summary between X and R in lines at 400 kV in Austria**

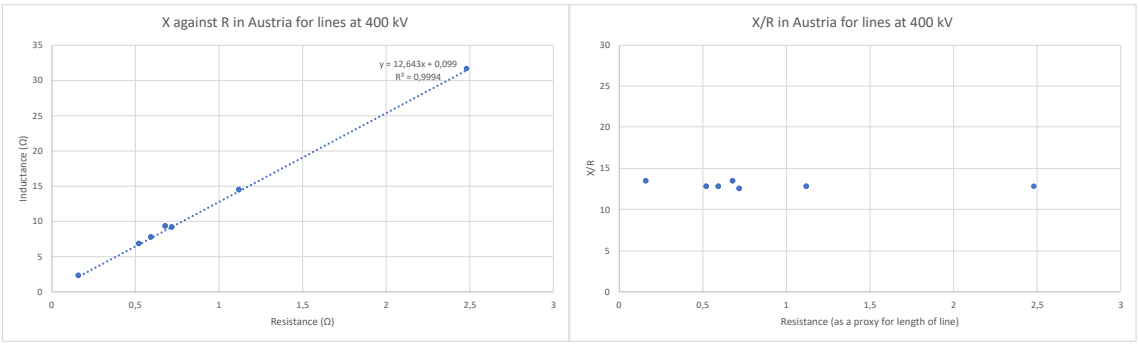



**Figure 150: Relation 1 between X and R in lines at 400 kV in Austria**

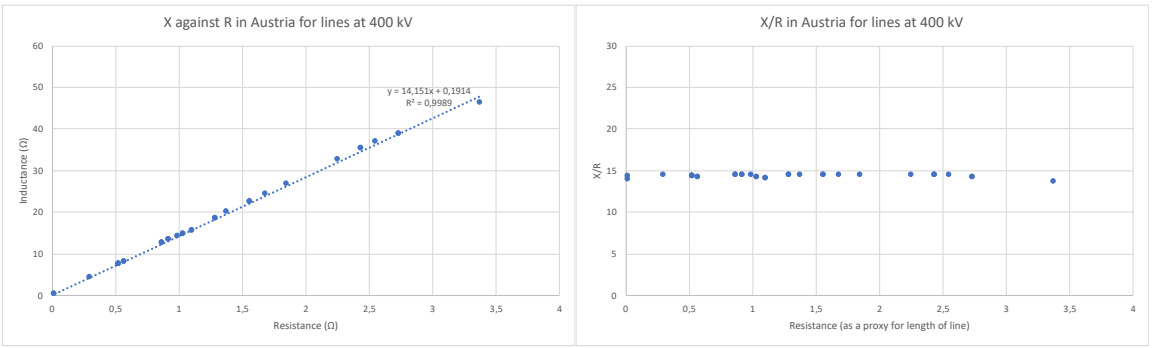



**Figure 151: Relation 2 between X and R in lines at 400 kV in Austria**

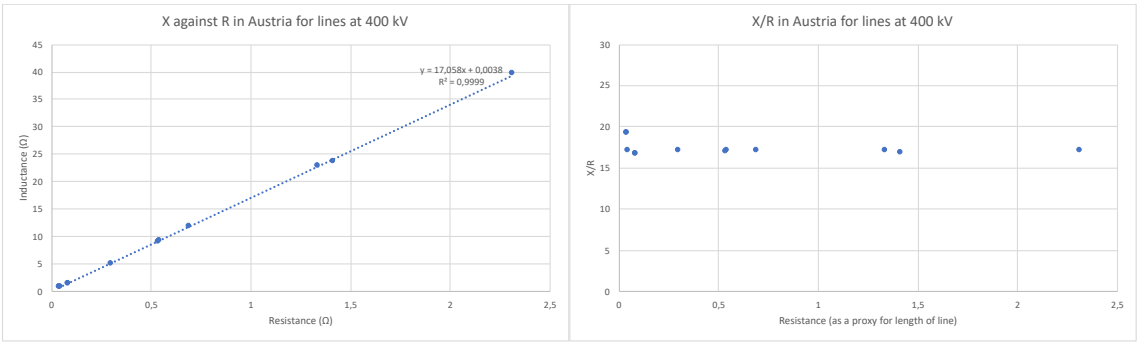



**Figure 152: Relation 3 between X and R in lines at 400 kV in Austria**

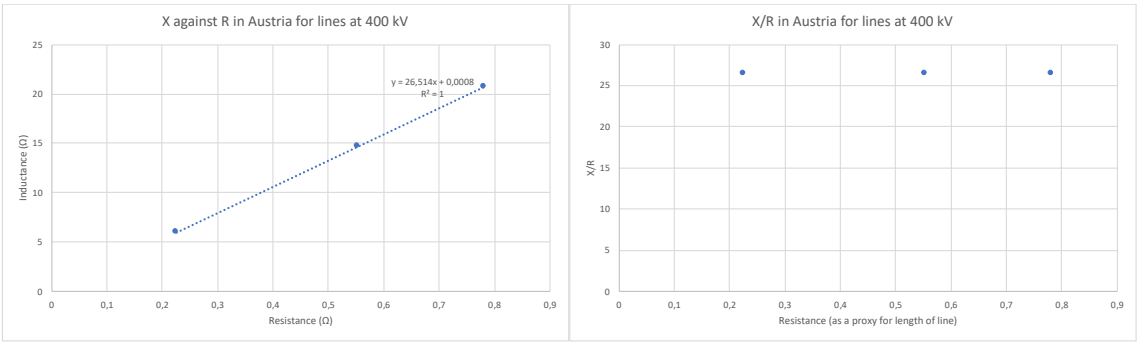



**Figure 153: Relation 4 between X and R in lines at 400 kV in Austria**

## Belgium

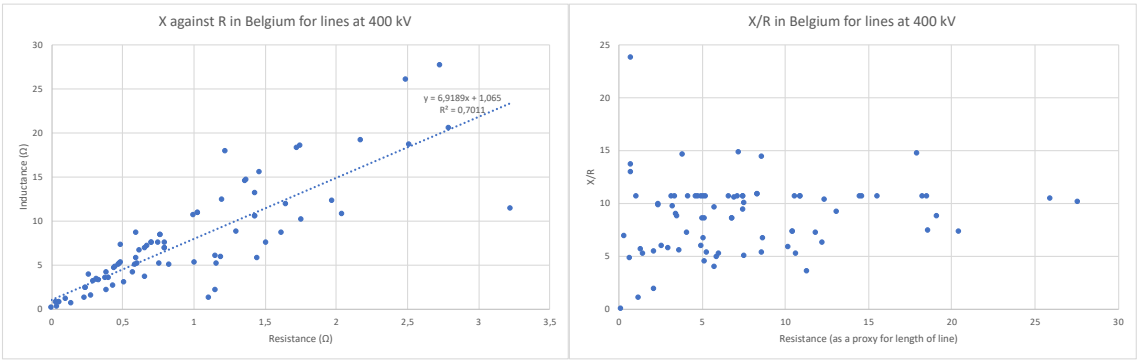



**Figure 154: Relation summary between X and R in lines at 400 kV in Belgium**

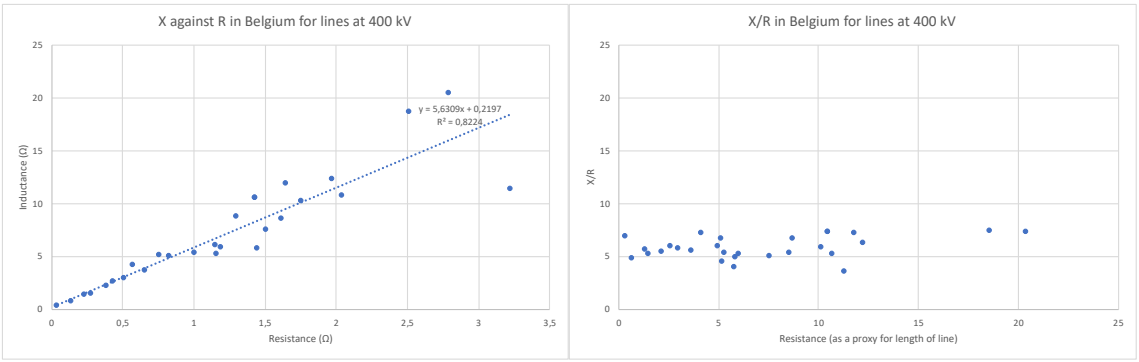



**Figure 155: Relation 1 between X and R in lines at 400 kV in Belgium**

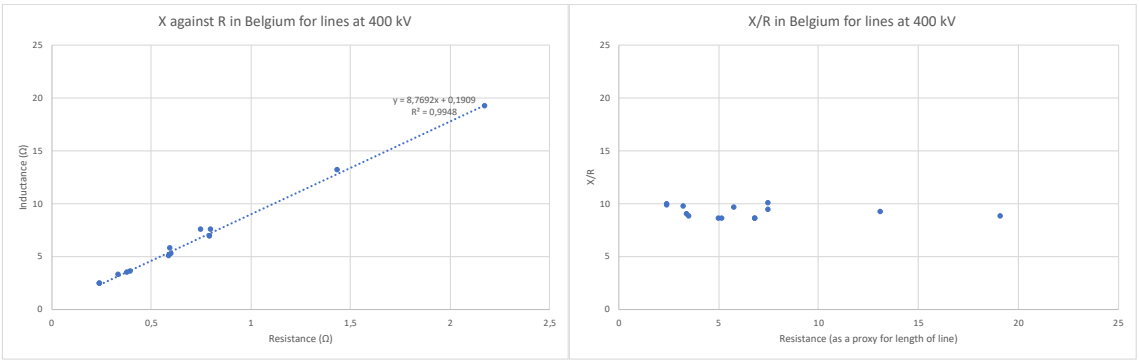



**Figure 156: Relation 2 between X and R in lines at 400 kV in Belgium**

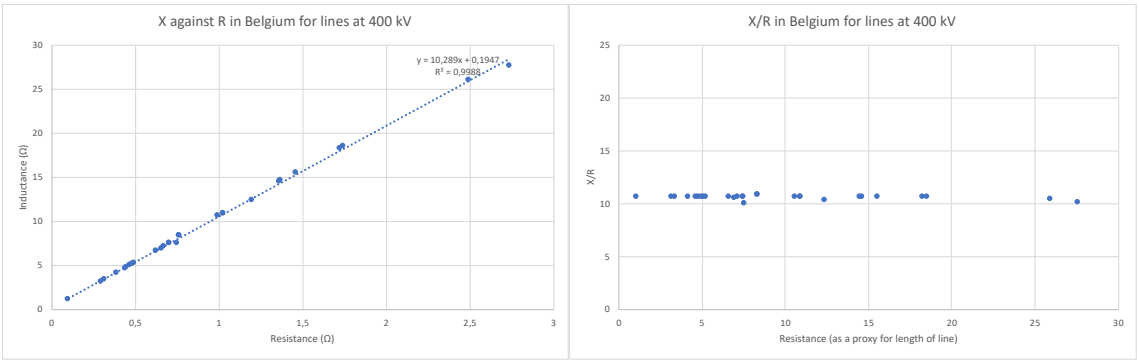



**Figure 157: Relation 3 between X and R in lines at 400 kV in Belgium**

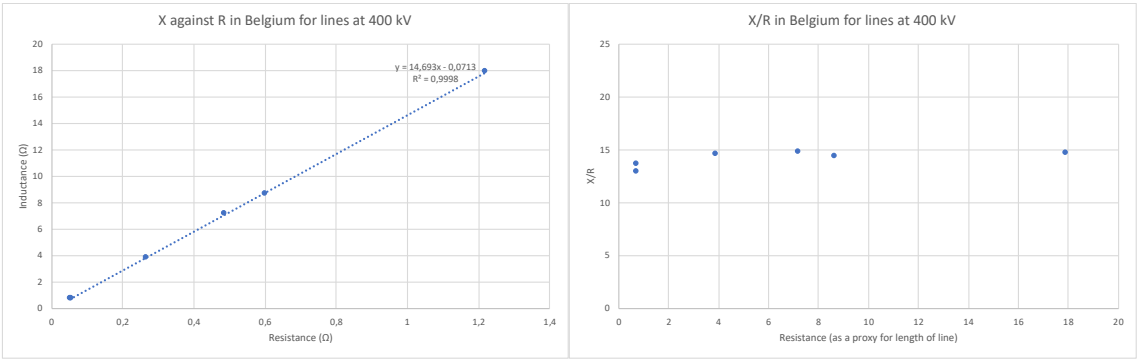



**Figure 158: Relation 4 between X and R in lines at 400 kV in Belgium**

## Bulgaria

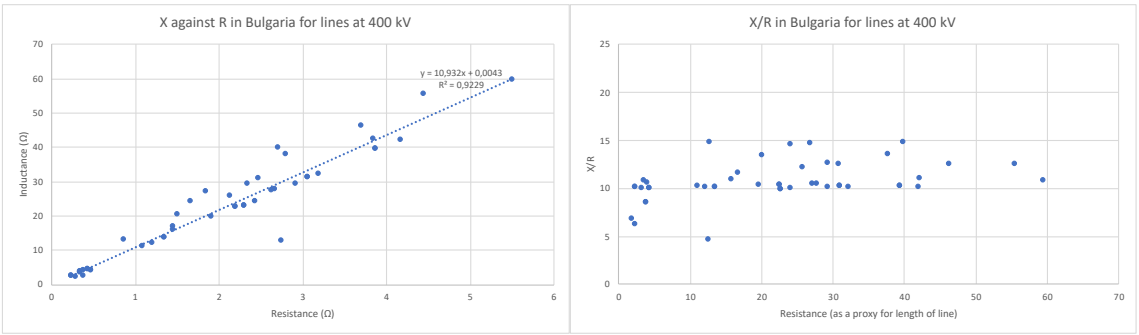



**Figure 159: Relation summary between X and R in lines at 400 kV in Bulgaria**

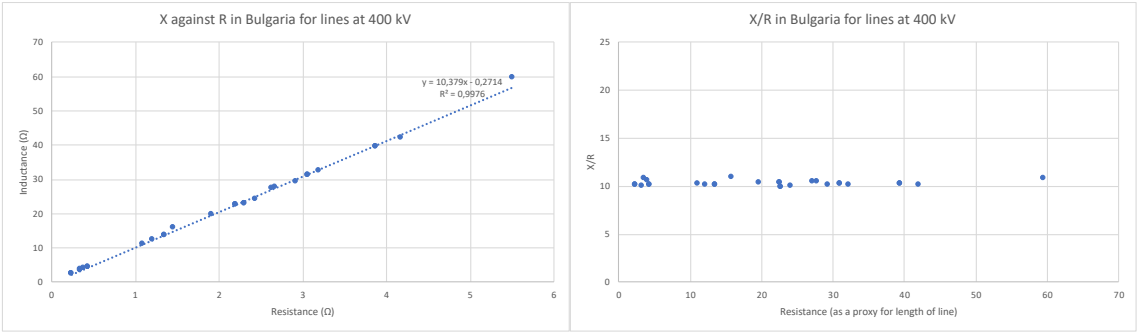



**Figure 160: Relation 1 between X and R in lines at 400 kV in Bulgaria**

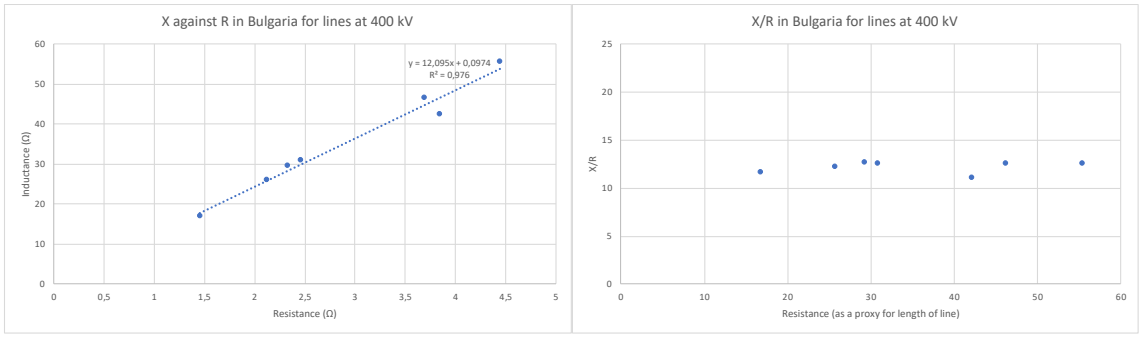



**Figure 161: Relation 2 between X and R in lines at 400 kV in Bulgaria**

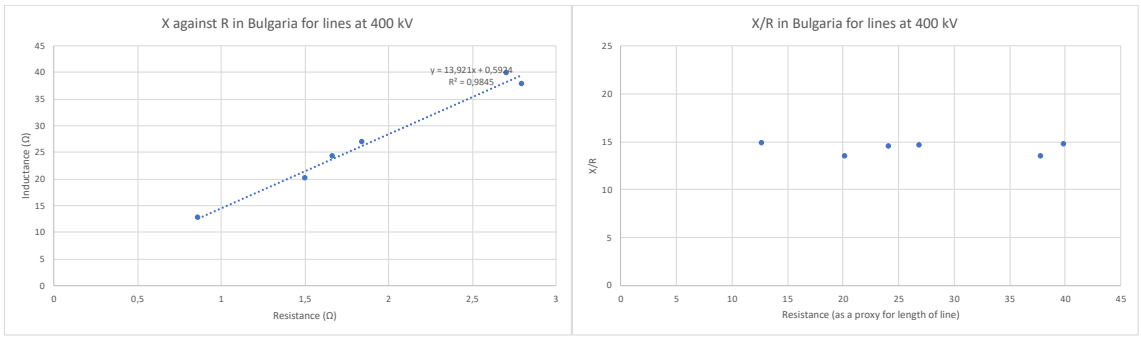



**Figure 162: Relation 3 between X and R in lines at 400 kV in Bulgaria**

## Switzerland

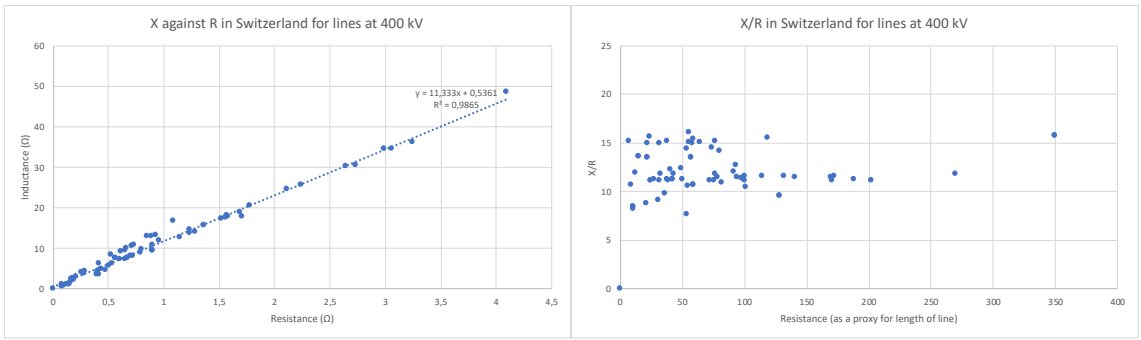



**Figure 163: Relation summary between X and R in lines at 400 kV in Switzerland**

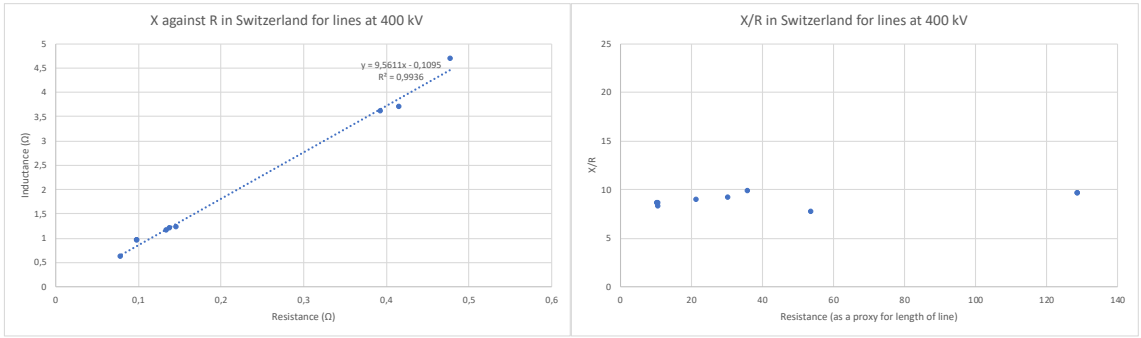



**Figure 164: Relation 1 between X and R in lines at 400 kV in Switzerland**

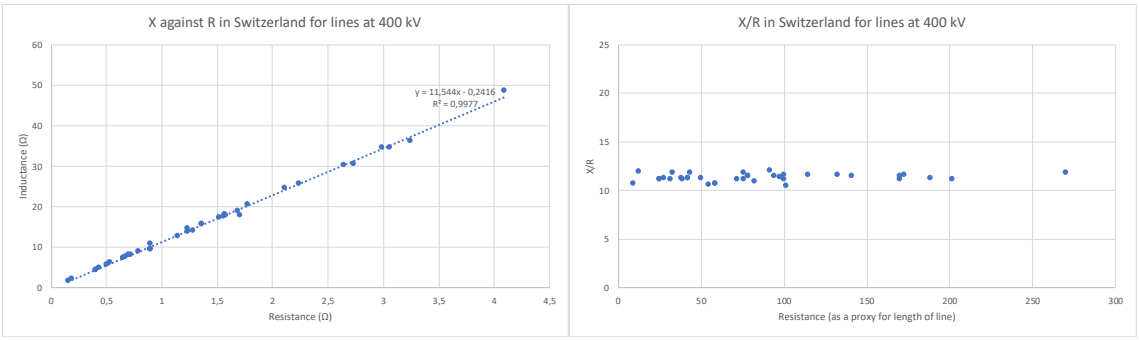



**Figure 165: Relation 2 between X and R in lines at 400 kV in Switzerland**

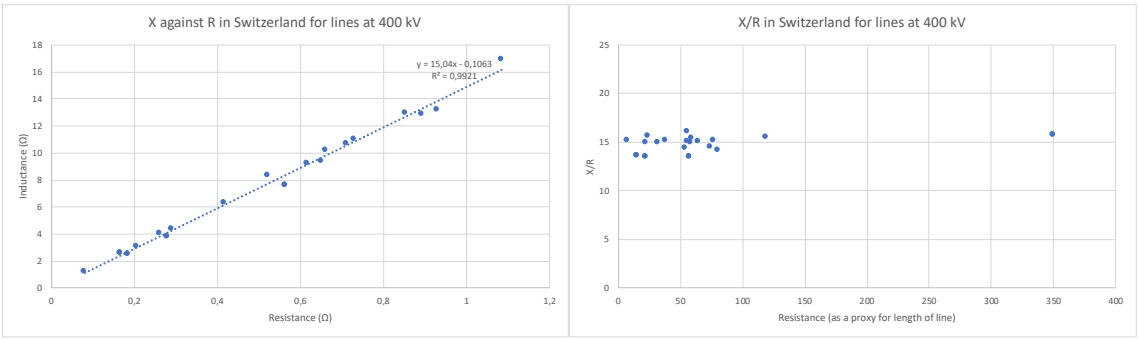



**Figure 166: Relation 3 between X and R in lines at 400 kV in Switzerland**

## Germany

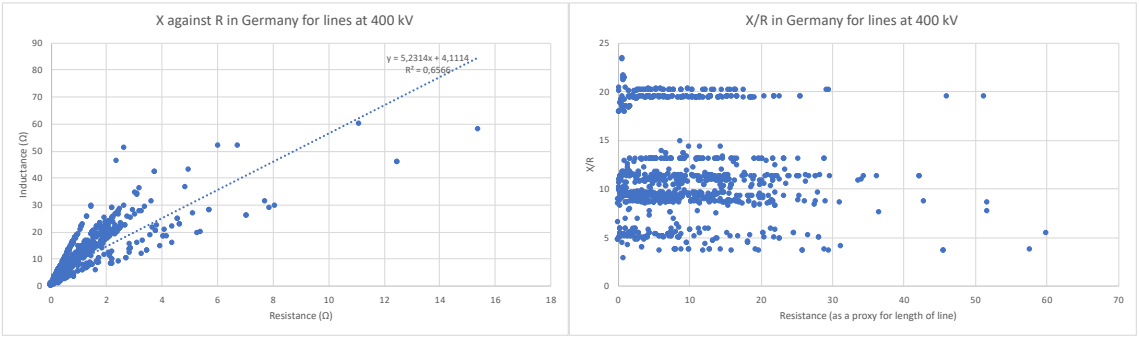



**Figure 167: Relation summary between X and R in lines at 400 kV in Germany**

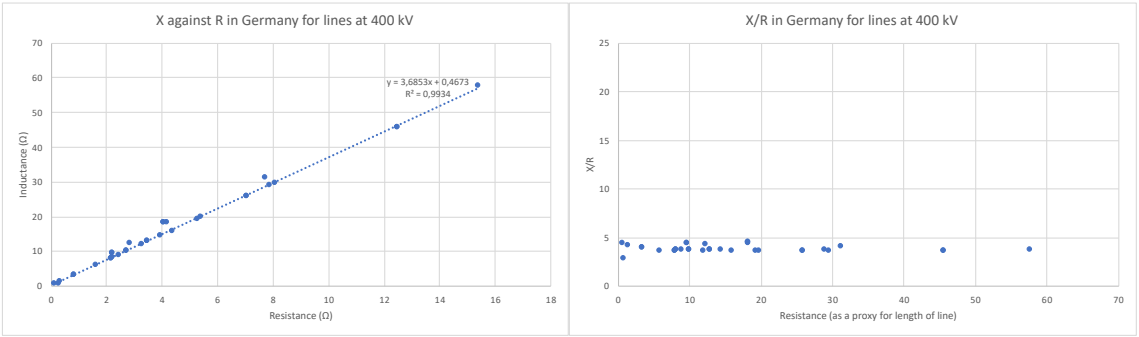



**Figure 168: Relation 1 between X and R in lines at 400 kV in Germany**

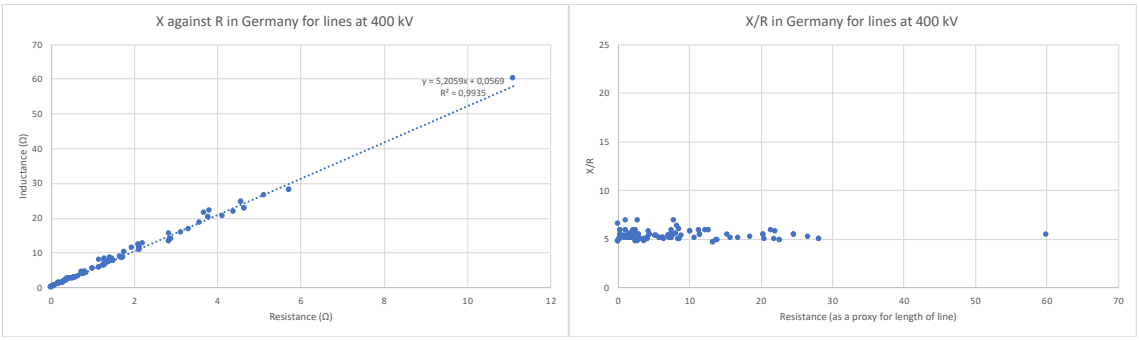



**Figure 169: Relation 2 between X and R in lines at 400 kV in Germany**

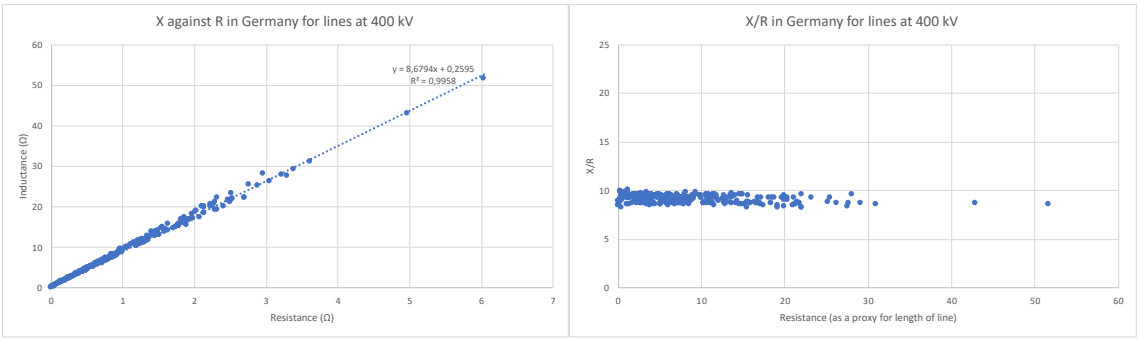



**Figure 170: Relation 3 between X and R in lines at 400 kV in Germany**

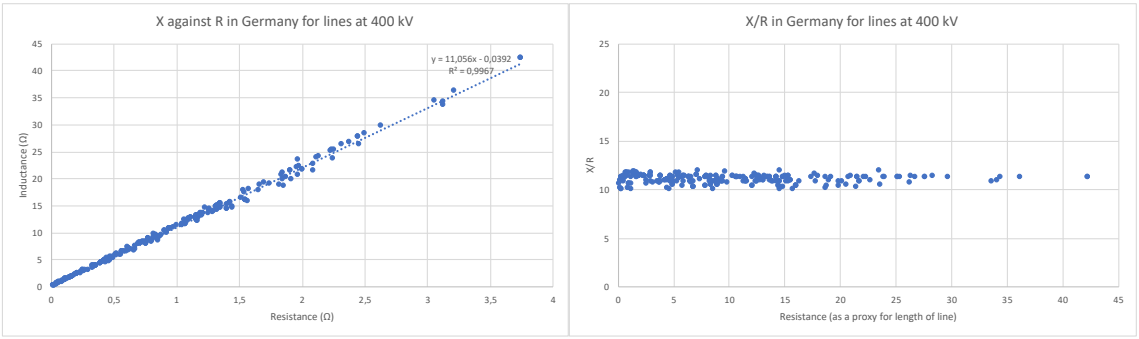



**Figure 171: Relation 4 between X and R in lines at 400 kV in Germany**

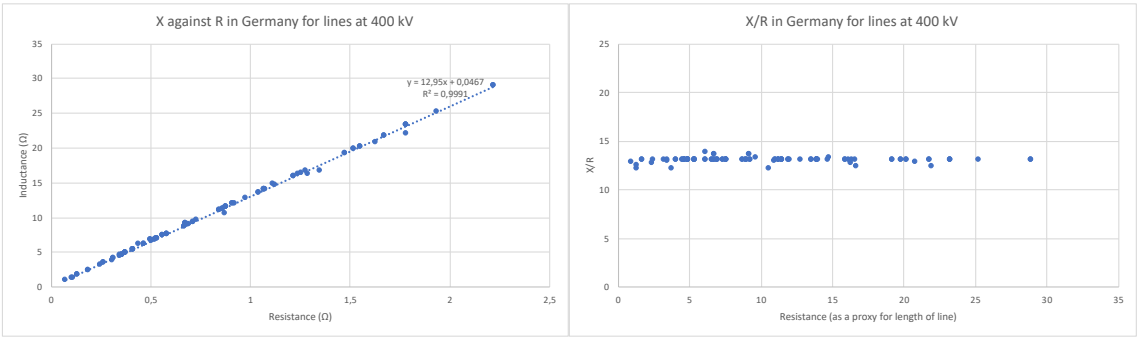



**Figure 172: Relation 5 between X and R in lines at 400 kV in Germany**

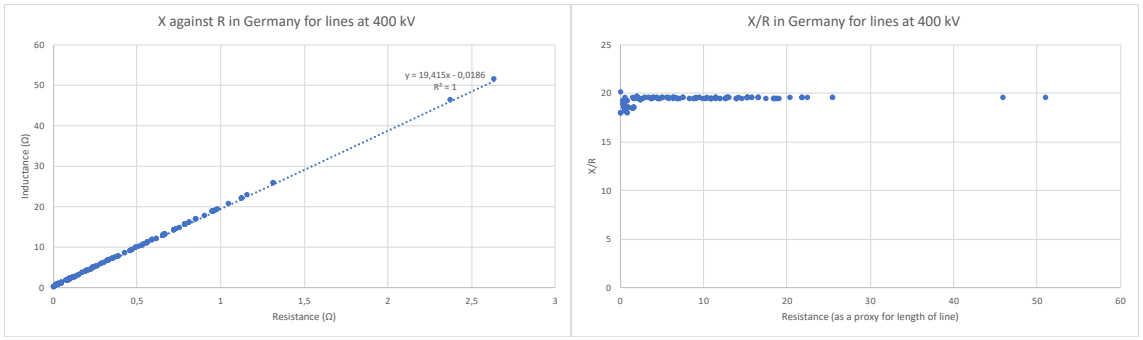



**Figure 173: Relation 6 between X and R in lines at 400 kV in Germany**

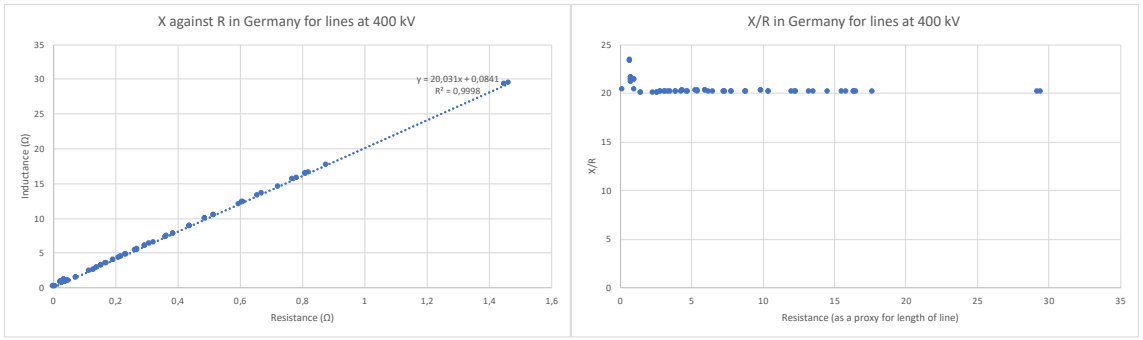



**Figure 174: Relation 7 between X and R in lines at 400 kV in Germany**

## Denmark

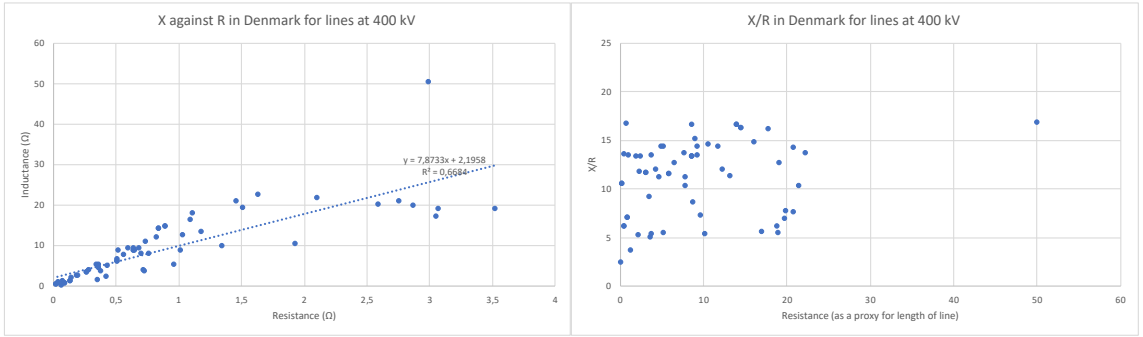



**Figure 175: Relation summary between X and R in lines at 400 kV in Denmark**

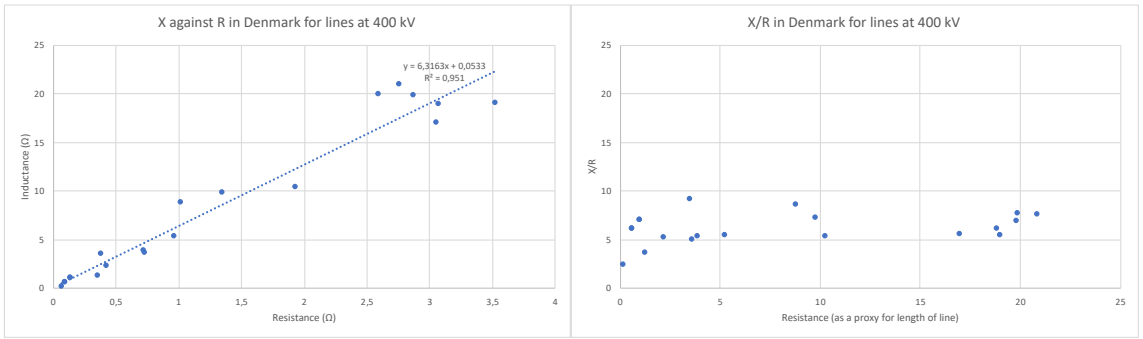



**Figure 176: Relation 1 between X and R in lines at 400 kV in Denmark**

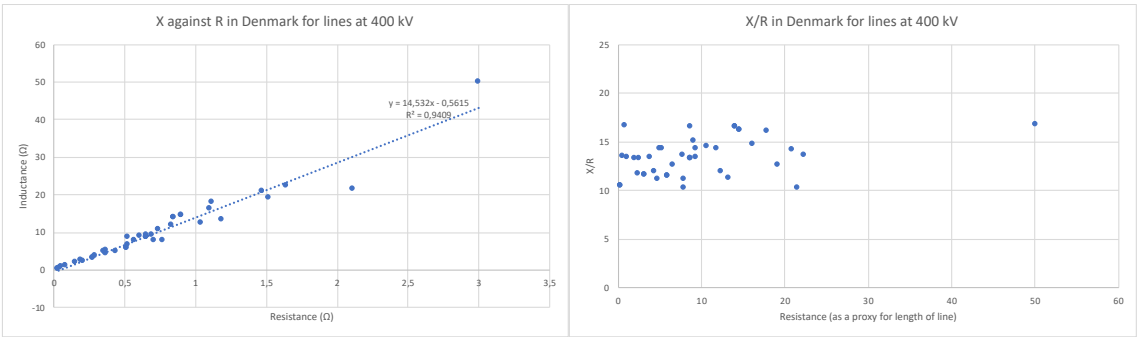



**Figure 177: Relation 2 between X and R in lines at 400 kV in Denmark**

## Spain

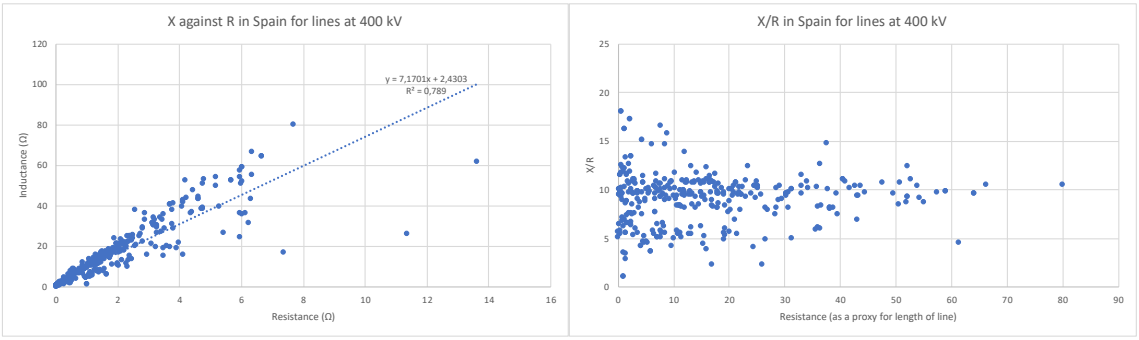



**Figure 178: Relation summary between X and R in lines at 400 kV in Spain**

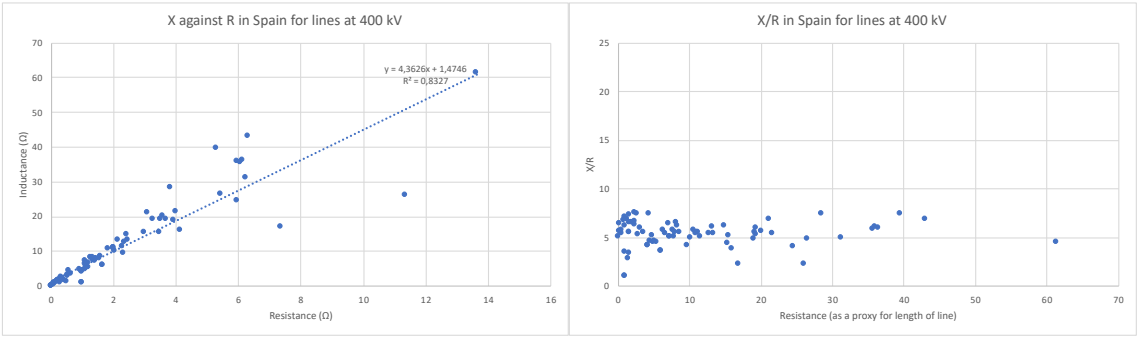



**Figure 179: Relation 1 between X and R in lines at 400 kV in Spain**

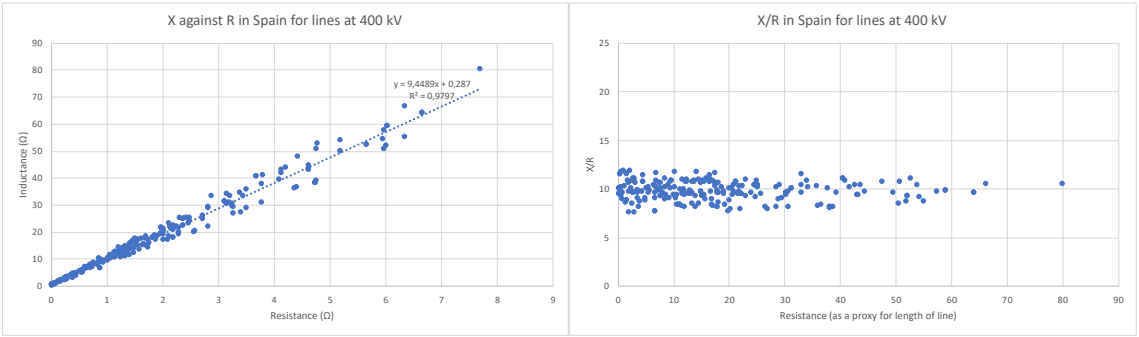



**Figure 180: Relation 2 between X and R in lines at 400 kV in Spain**

## France

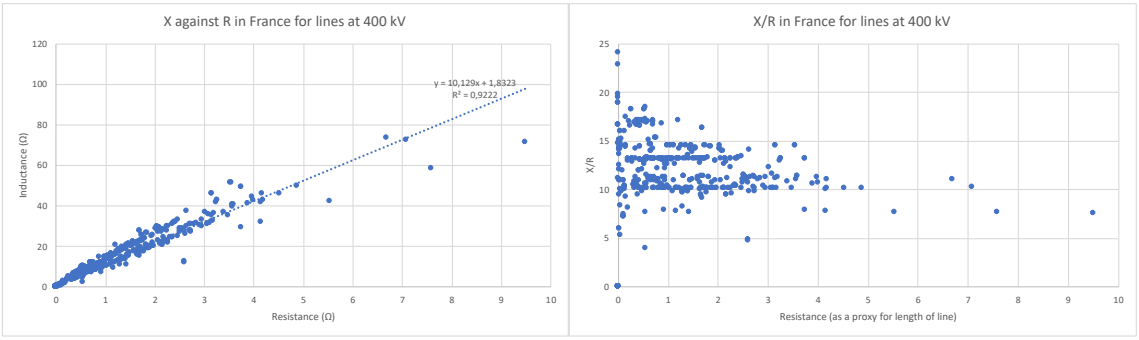



**Figure 181: Relation summary between X and R in lines at 400 kV in France**

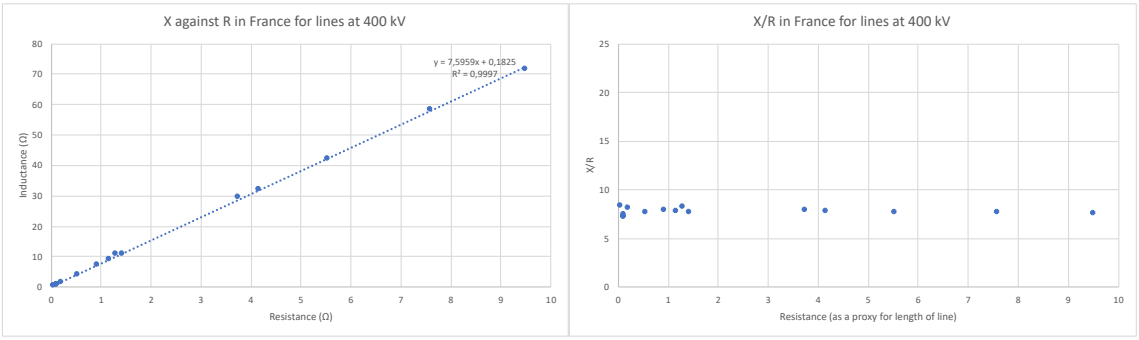



**Figure 182: Relation 1 between X and R in lines at 400 kV in France**

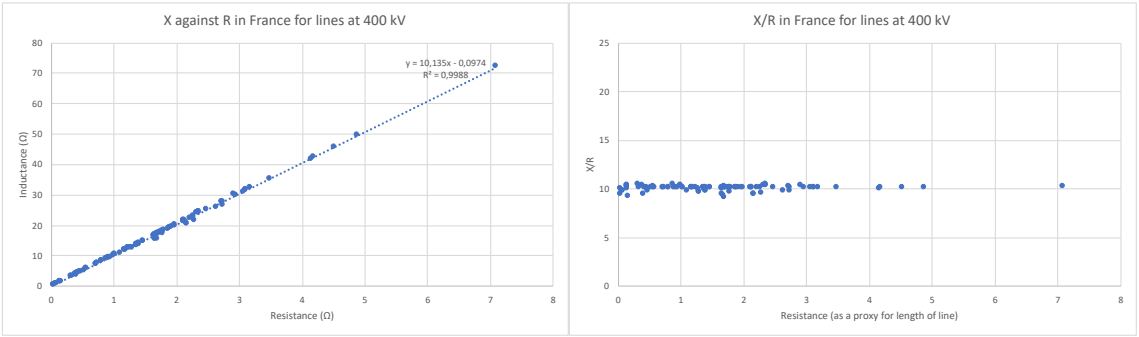



**Figure 183: Relation 2 between X and R in lines at 400 kV in France**

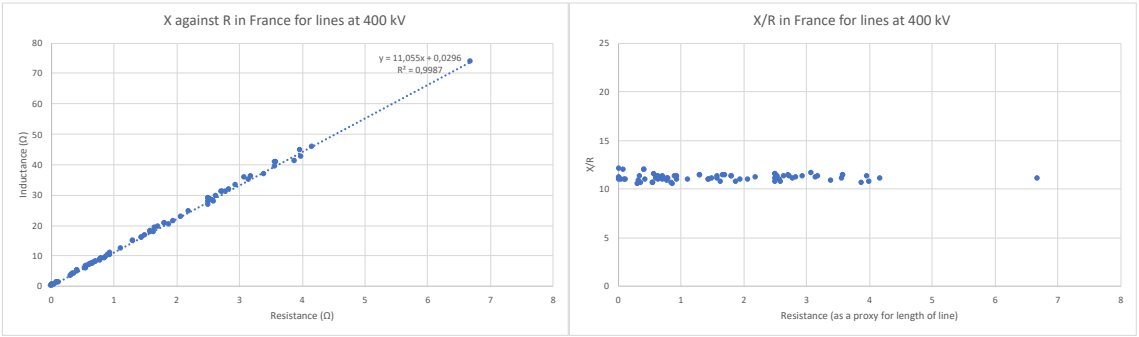



**Figure 184: Relation 3 between X and R in lines at 400 kV in France**

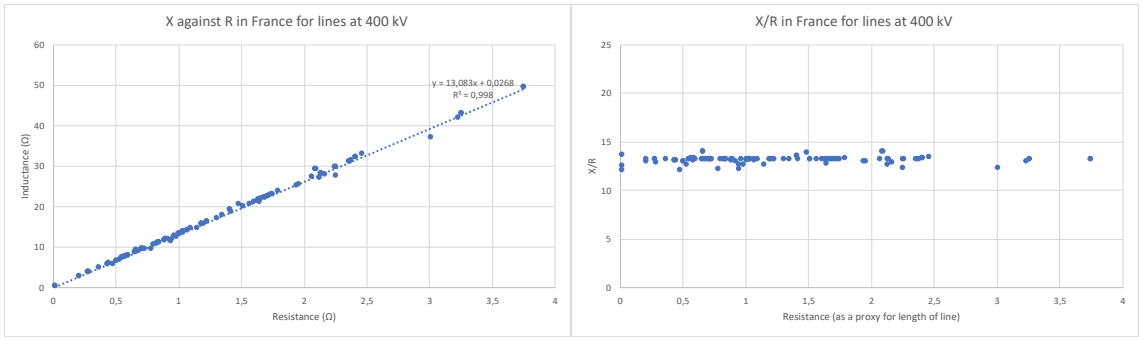



**Figure 185: Relation 4 between X and R in lines at 400 kV in France**

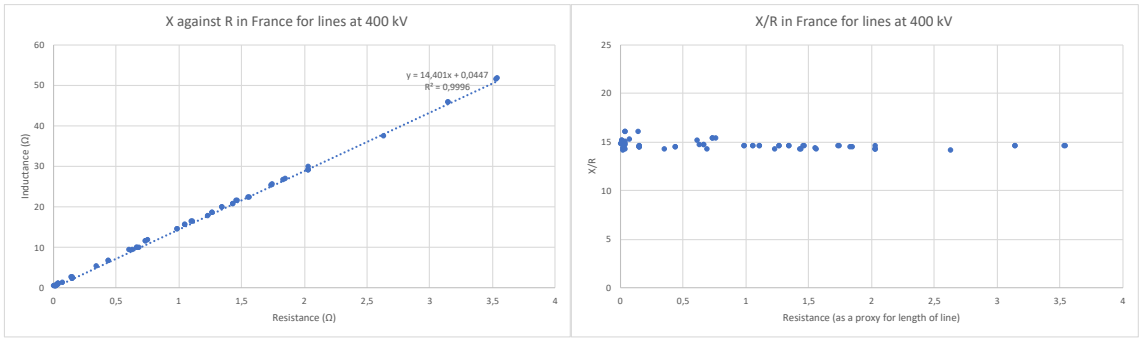



**Figure 186: Relation 5 between X and R in lines at 400 kV in France**

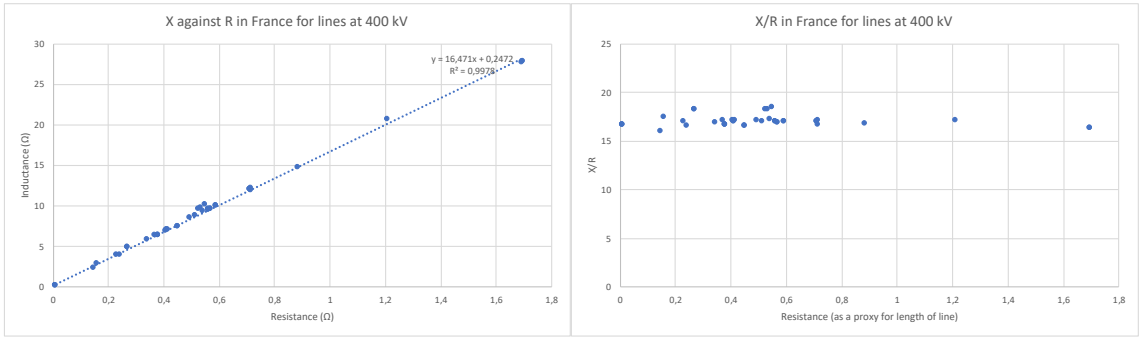



**Figure 187: Relation 6 between X and R in lines at 400 kV in France**

## Greece

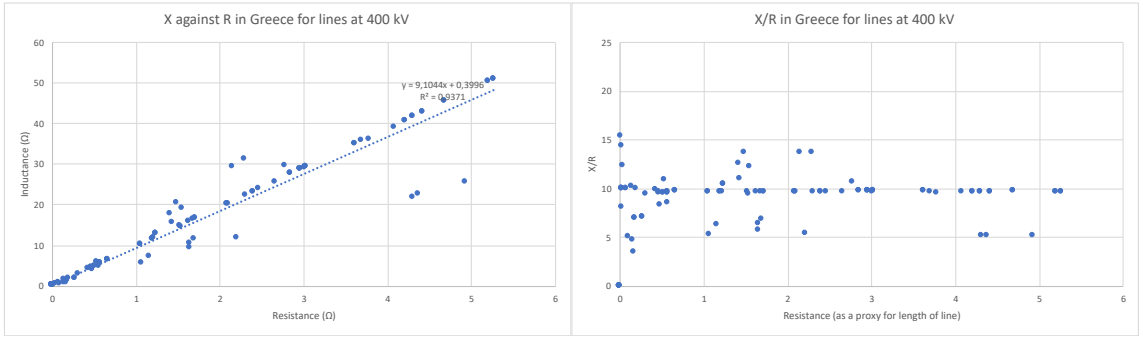



**Figure 188: Relation summary between X and R in lines at 400 kV in Greece**

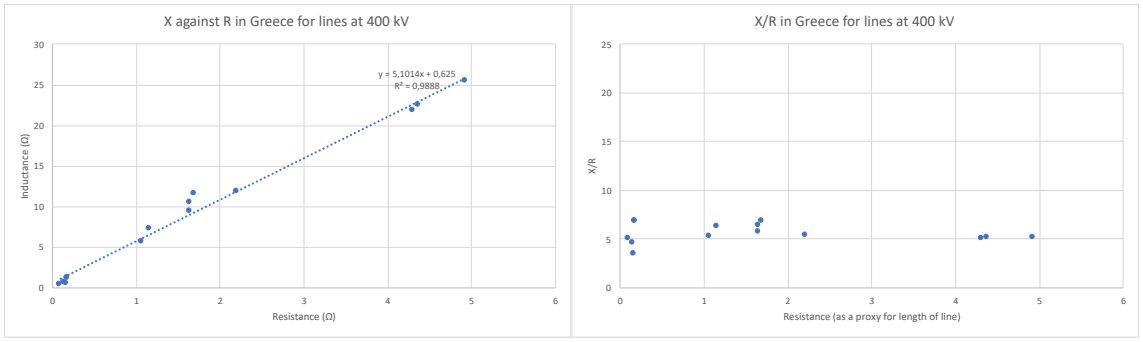



**Figure 189: Relation 1 between X and R in lines at 400 kV in Greece**

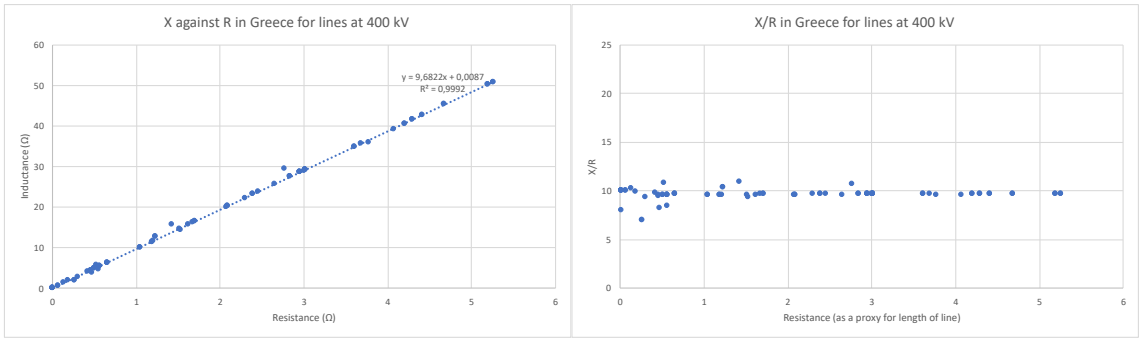



**Figure 190: Relation 2 between X and R in lines at 400 kV in Greece**

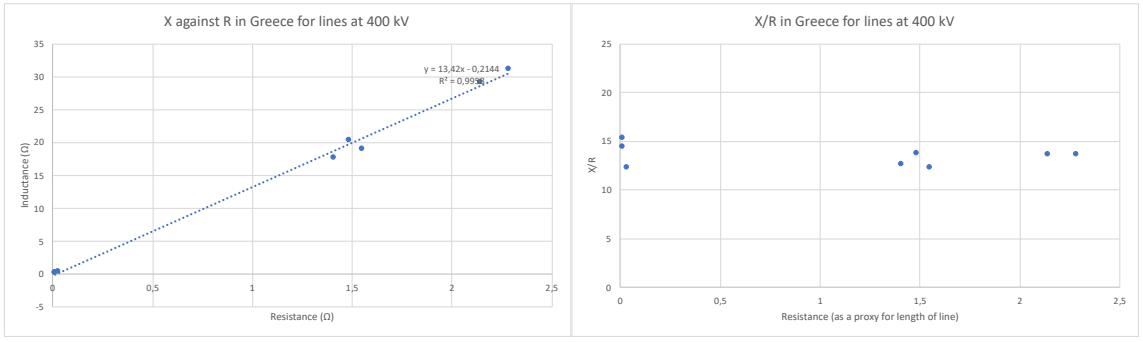



**Figure 191: Relation 3 between X and R in lines at 400 kV in Greece**

## Hungary

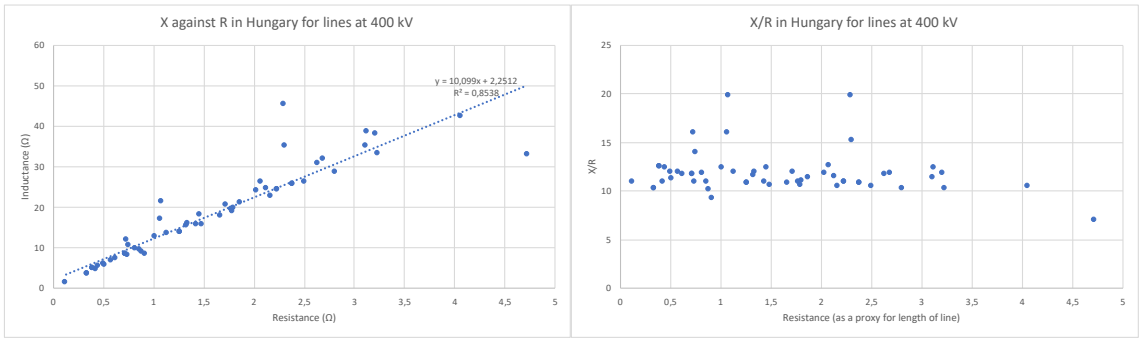



**Figure 192: Relation summary between X and R in lines at 400 kV in Hungary**

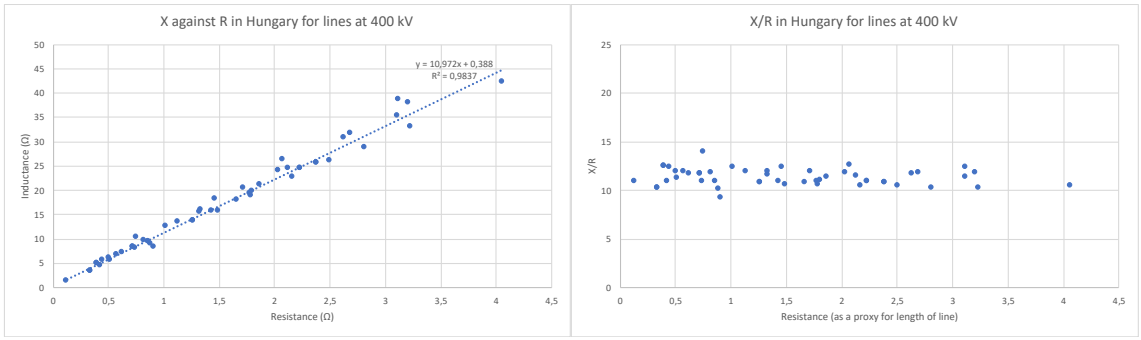



**Figure 193: Relation 1 between X and R in lines at 400 kV in Hungary**

# Italy

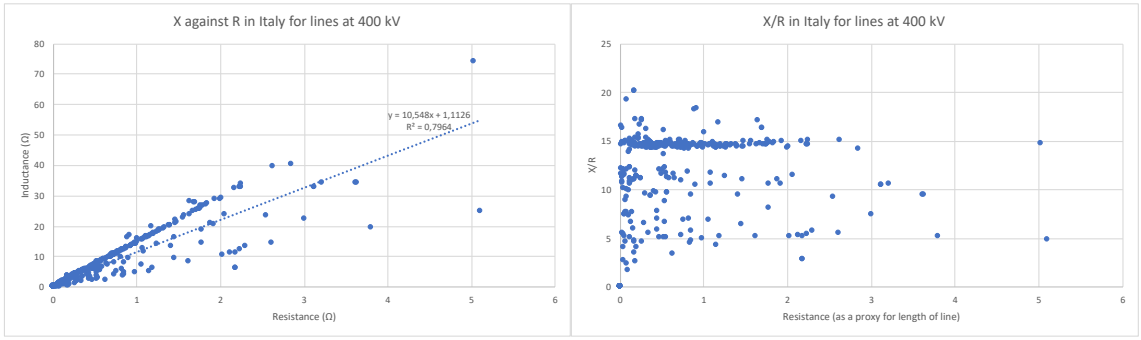



**Figure 194: Relation summary between X and R in lines at 400 kV in Italy**

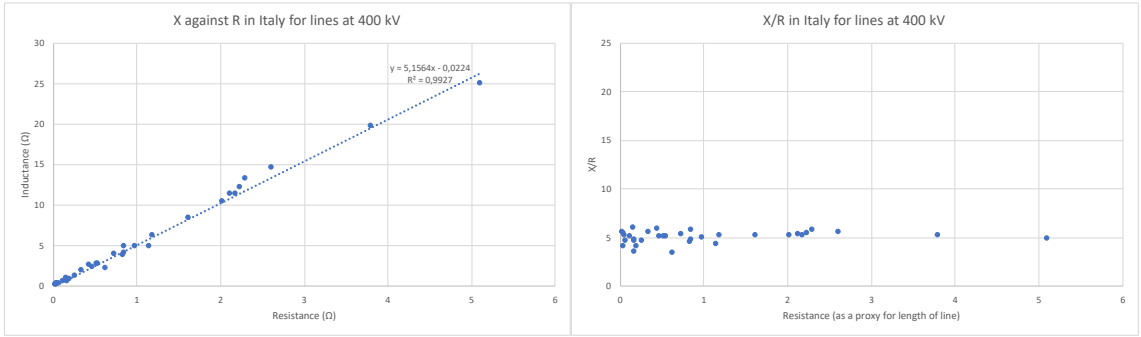



**Figure 195: Relation 1 between X and R in lines at 400 kV in Italy**

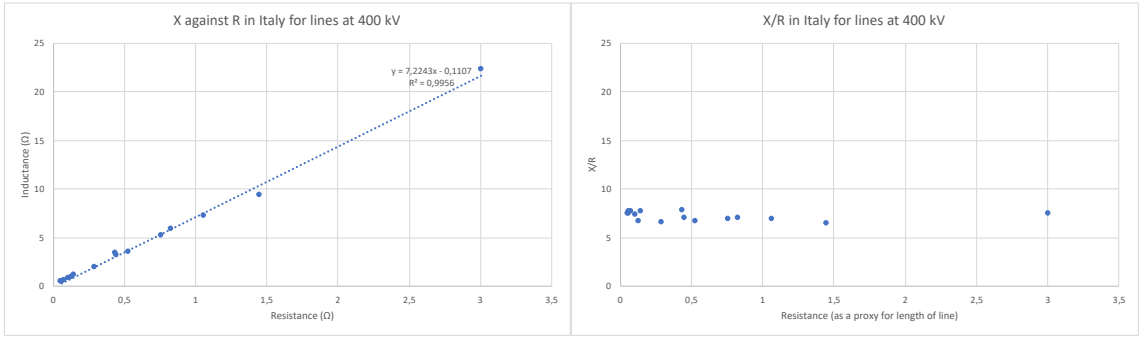



**Figure 196: Relation 2 between X and R in lines at 400 kV in Italy**

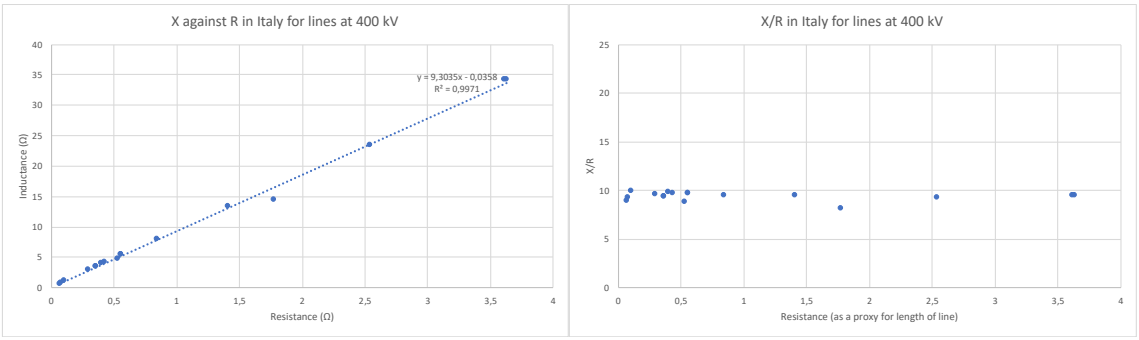



**Figure 197: Relation 3 between X and R in lines at 400 kV in Italy**

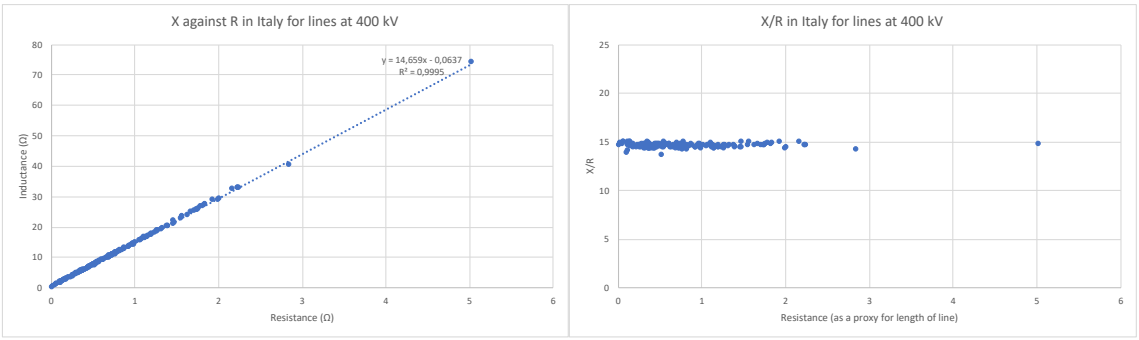



**Figure 198: Relation 4 between X and R in lines at 400 kV in Italy**

## Netherlands

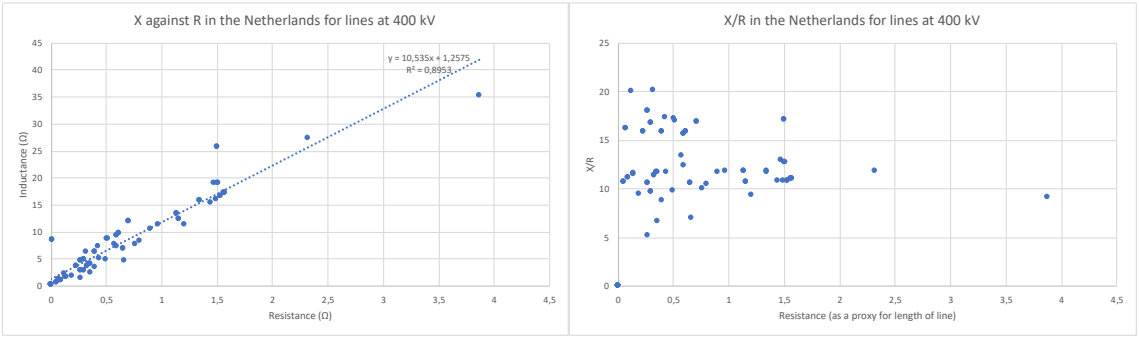



**Figure 199: Relation summary between X and R in lines at 400 kV in the Netherlands**

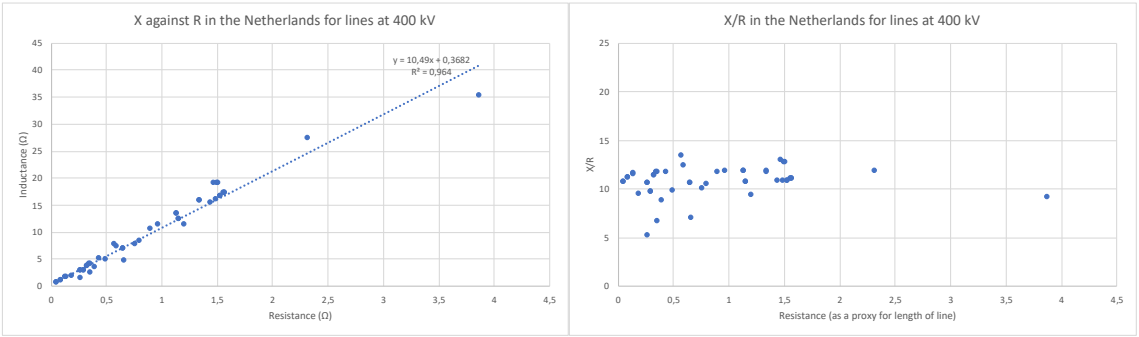



**Figure 200: Relation 1 between X and R in lines at 400 kV in the Netherlands**

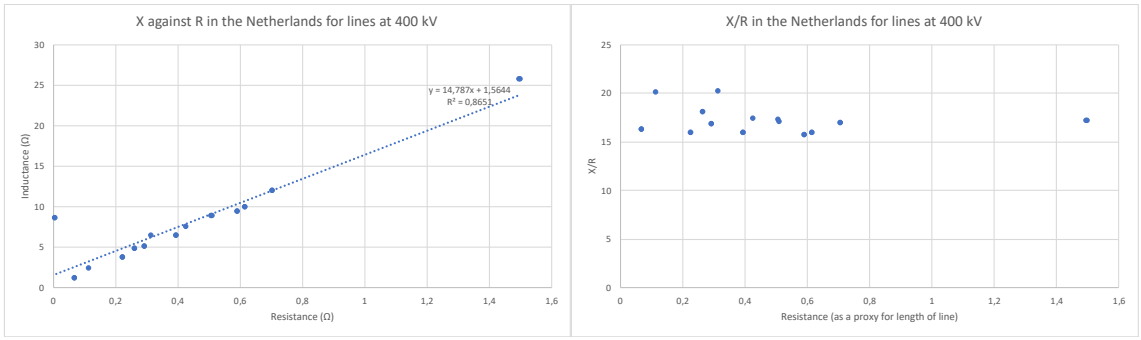



**Figure 201: Relation 2 between X and R in lines at 400 kV in the Netherlands**

## Poland

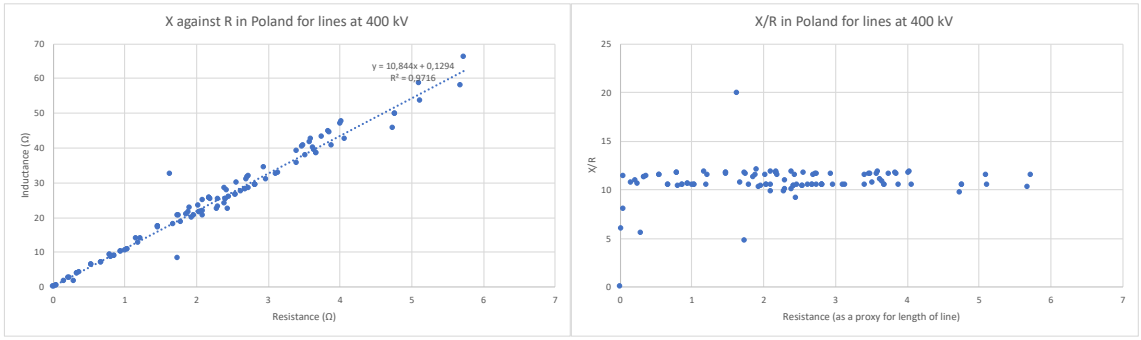



**Figure 202: Relation summary between X and R in lines at 400 kV in Poland**

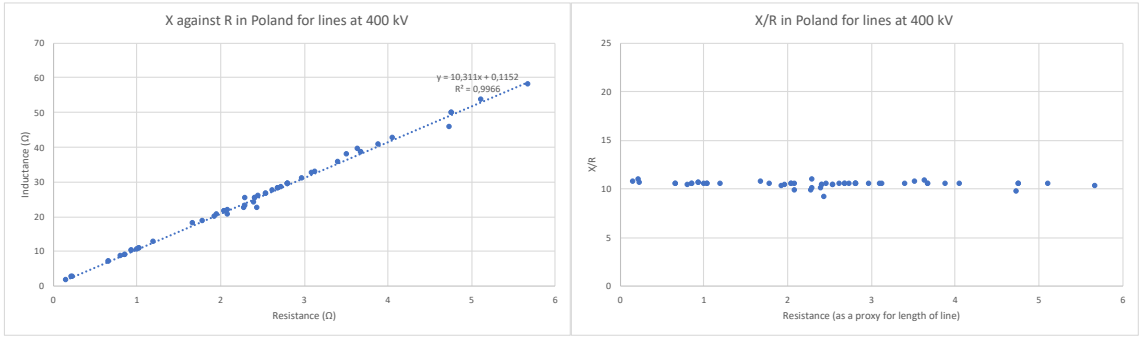



**Figure 203: Relation 1 between X and R in lines at 400 kV in Poland**

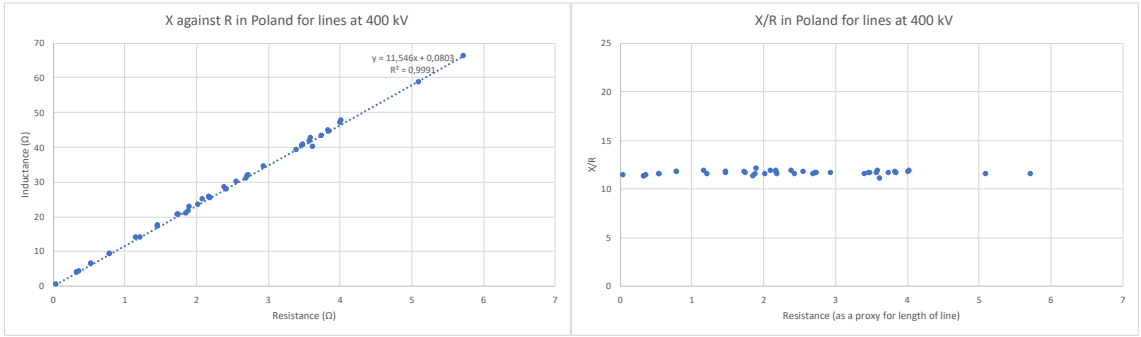



**Figure 204: Relation 2 between X and R in lines at 400 kV in Poland**

# Portugal

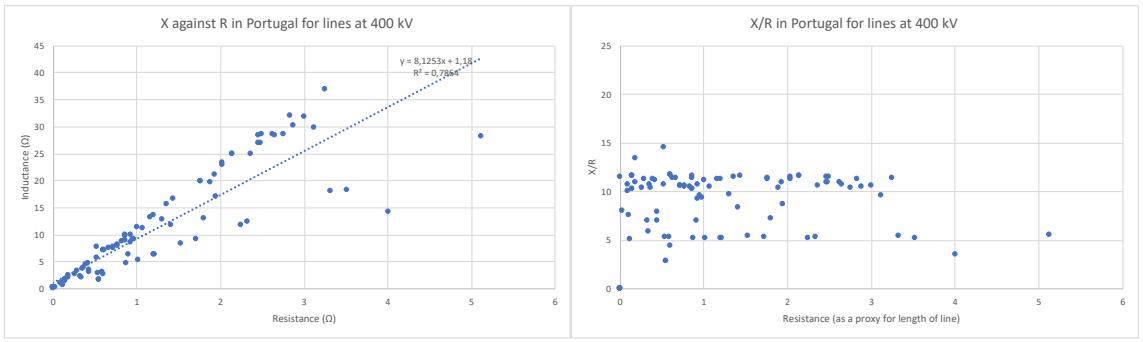



**Figure 205: Relation summary between X and R in lines at 400 kV in Portugal**

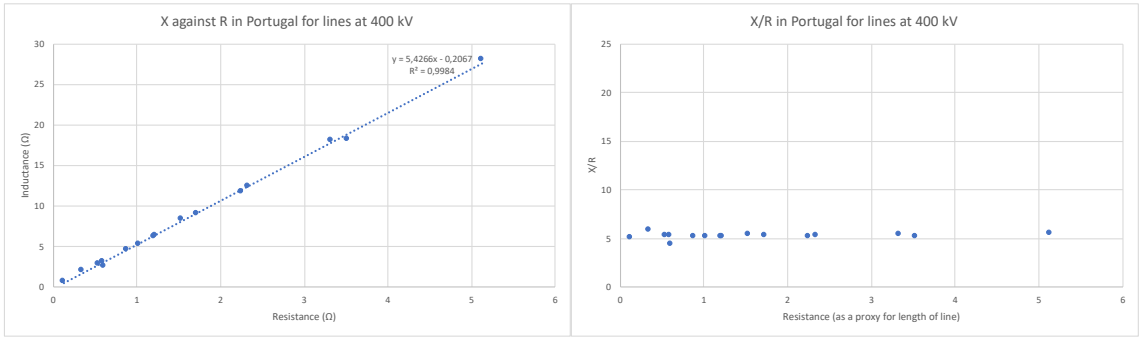



**Figure 206: Relation 1 between X and R in lines at 400 kV in Portugal**

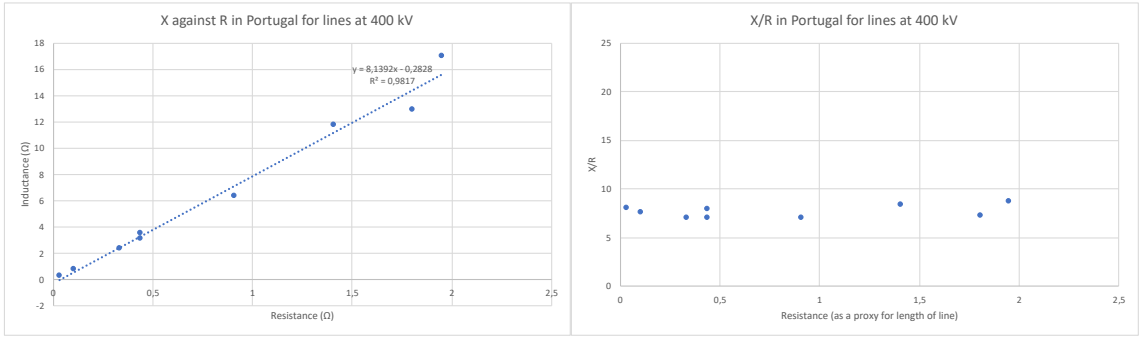



**Figure 207: Relation 2 between X and R in lines at 400 kV in Portugal**

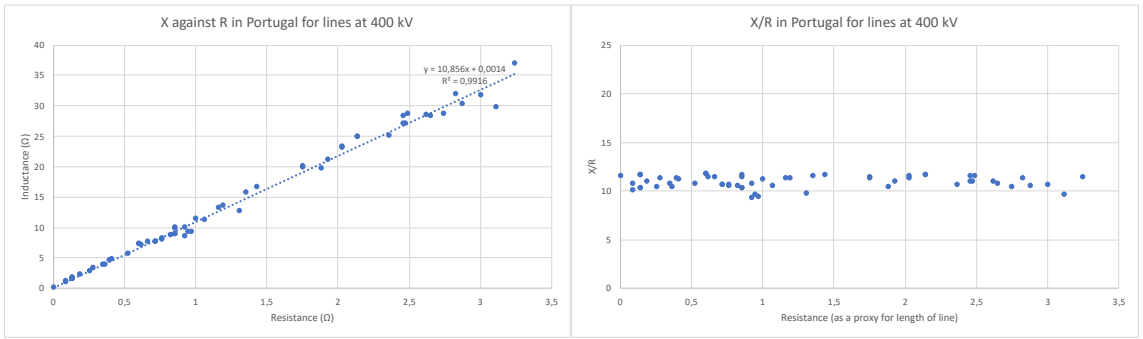



**Figure 208: Relation 3 between X and R in lines at 400 kV in Portugal**

## Romania

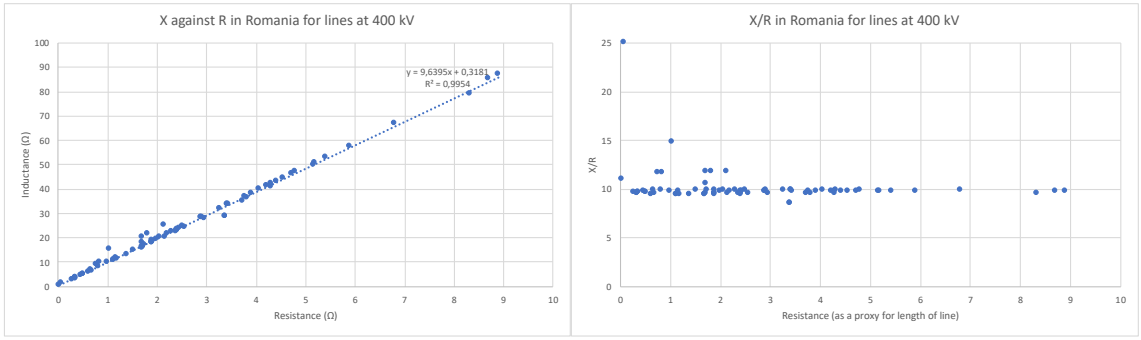



**Figure 209: Relation summary between X and R in lines at 400 kV in Romania**

## Russia

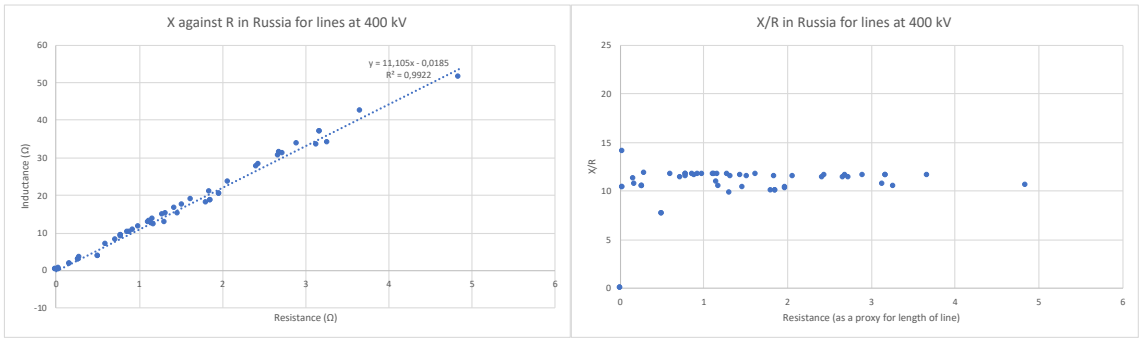



**Figure 210: Relation summary between X and R in lines at 400 kV in Russia**

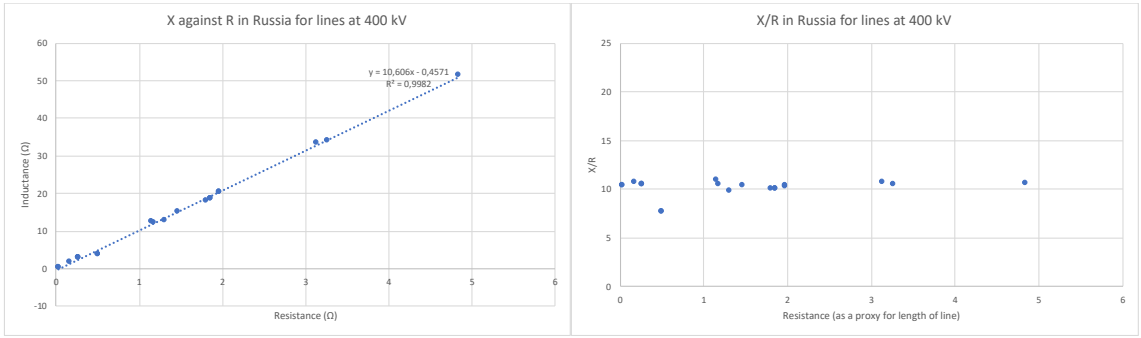



**Figure 211: Relation 1 between X and R in lines at 400 kV in Russia**

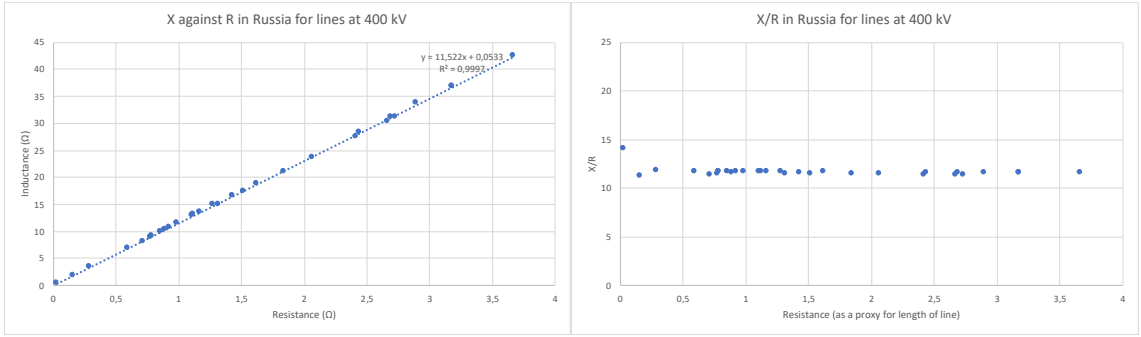
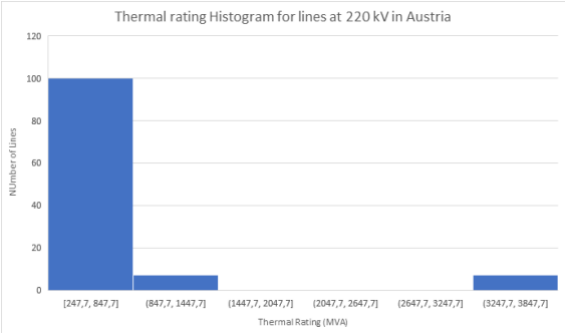
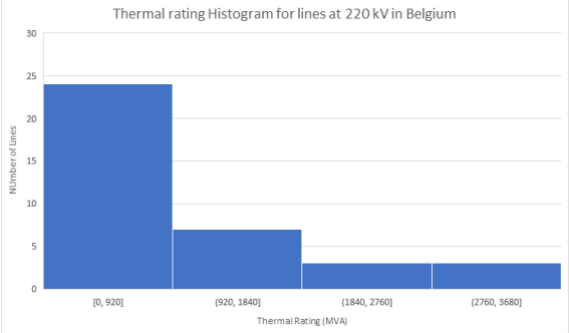


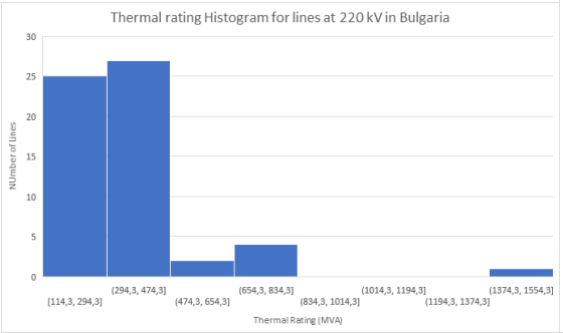

**Figure 212: Relation 2 between X and R in lines at 400 kV in Russia**

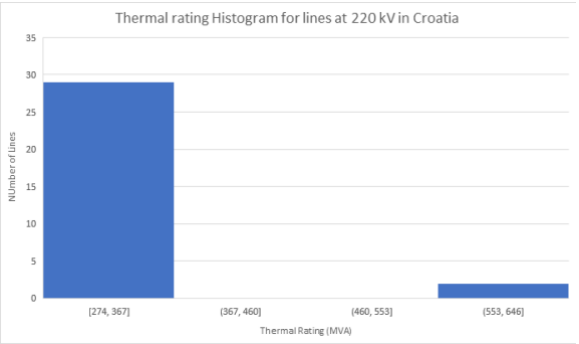
## 9.3. Thermal Rating Histograms

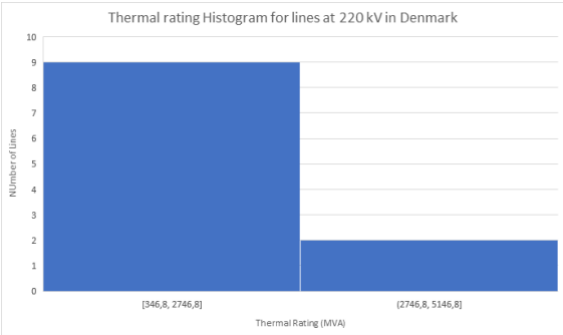
### 9.3.1. 220 kV



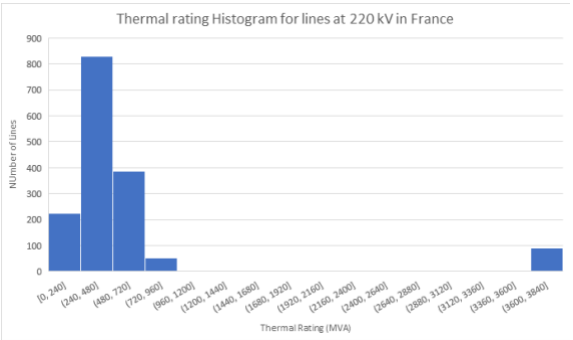
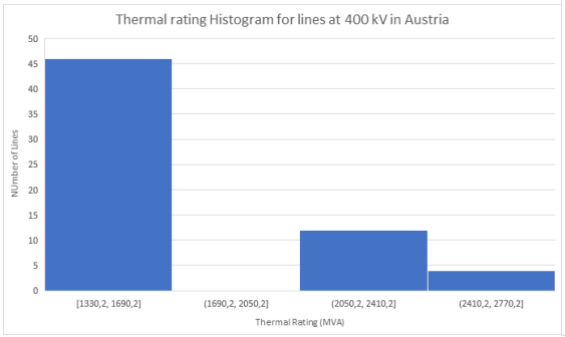
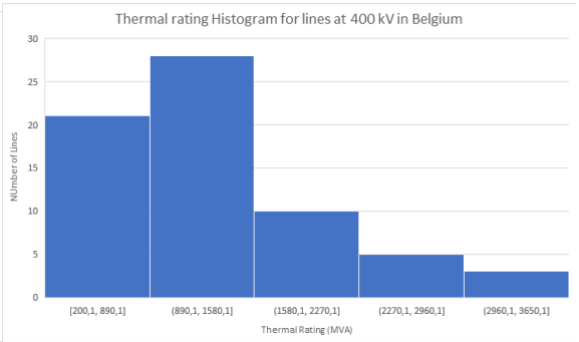



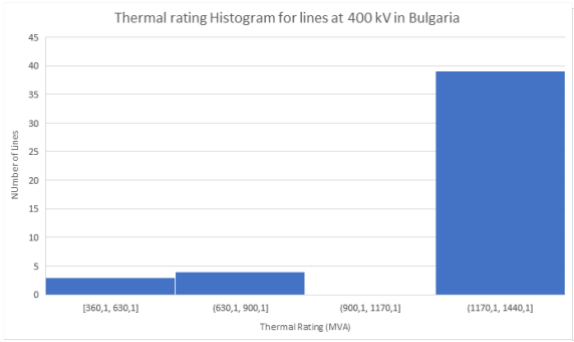


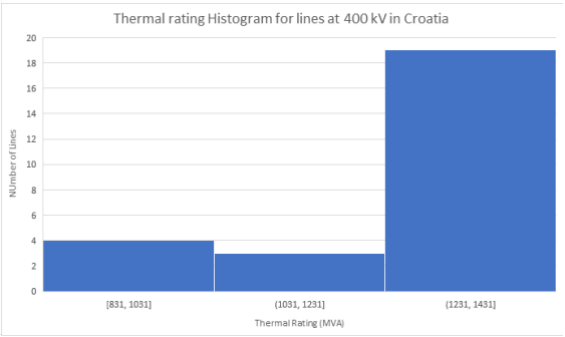

**Figure 213: Thermal rating histograms for European countries at 220 kV**

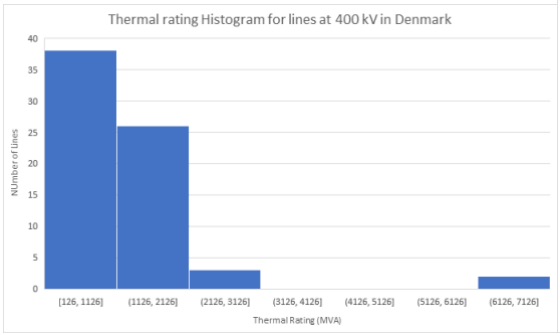
### 9.3.2. 400 kV

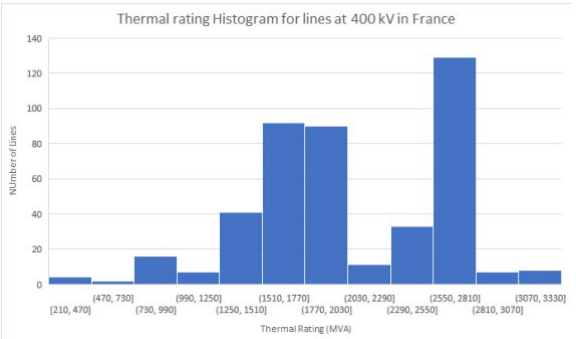

Thermal rating Histogram for lines at 400 kV in Austria
NUmber of Lines
Thermal Rating (MVA)
[1330,2, 1690,2]
(1690,2, 2050,2]
(2050,2, 2410,2]
(2410,2, 2770,2]

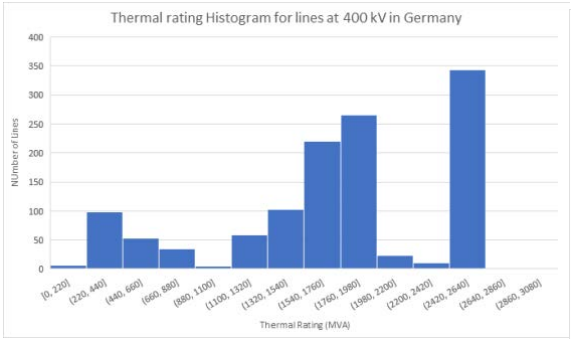

Thermal rating Histogram for lines at 400 kV in Belgium
NUmber of Lines
Thermal Rating (MVA)
[200,1, 890,1]
(890,1, 1580,1]
(1580,1, 2270,1]
(2270,1, 2960,1]
(2960,1, 3650,1]

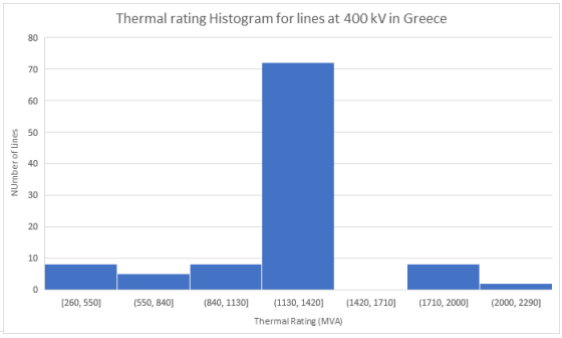

Thermal rating Histogram for lines at 400 kV in Bulgaria
NUmber of Lines
Thermal Rating (MVA)
[360,1, 630,1]
(630,1, 900,1]
(900,1, 1170,1]
(1170,1, 1440,1]


Thermal rating Histogram for lines at 400 kV in Croatia
NUmber of Lines
Thermal Rating (MVA)
[831, 1031]
(1031, 1231]
(1231, 1431]


Thermal rating Histogram for lines at 400 kV in Denmark
NUmber of Lines
Thermal Rating (MVA)
(126, 1126]
(1126, 2126]
(2126, 3126]
(3126, 4126]
(4126, 5126]
(5126, 6126]
(6126, 7126]


Thermal rating Histogram for lines at 400 kV in France
NUmber of Lines
Thermal Rating (MVA)
[210, 470]
(470, 730]
(730, 990]
(990, 1250]
(1250, 1510]
(1510, 1770]
(1770, 2030]
(2030, 2290]
(2290, 2550]
(2550, 2810]
(2810, 3070]
(3070, 3330]


Thermal rating Histogram for lines at 400 kV in Germany
NUmber of Lines
Thermal Rating (MVA)
[0, 220]
(220, 440]
(440, 660]
(660, 880]
(880, 1100]
(1100, 1320]
(1320, 1540]
(1540, 1760]
(1760, 1980]
(1980, 2200]
(2200, 2420]
(2420, 2640]
(2640, 2860]
(2860, 3080]


Thermal rating Histogram for lines at 400 kV in Greece
NUmber of Lines
Thermal Rating (MVA)
[260, 550]
(550, 840]
(840, 1130]
(1130, 1420]
(1420, 1710]
(1710, 2000]
(2000, 2290]

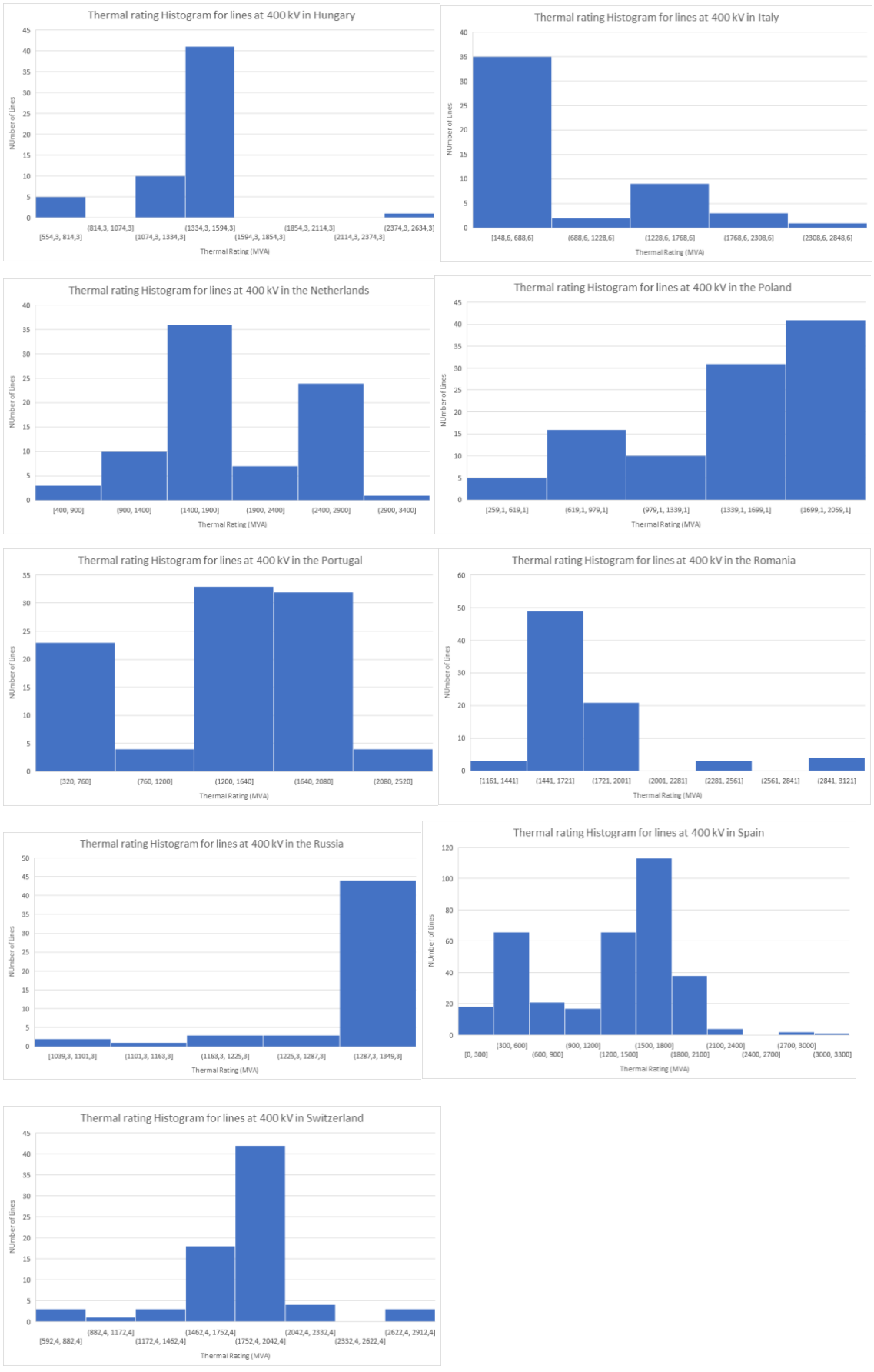



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